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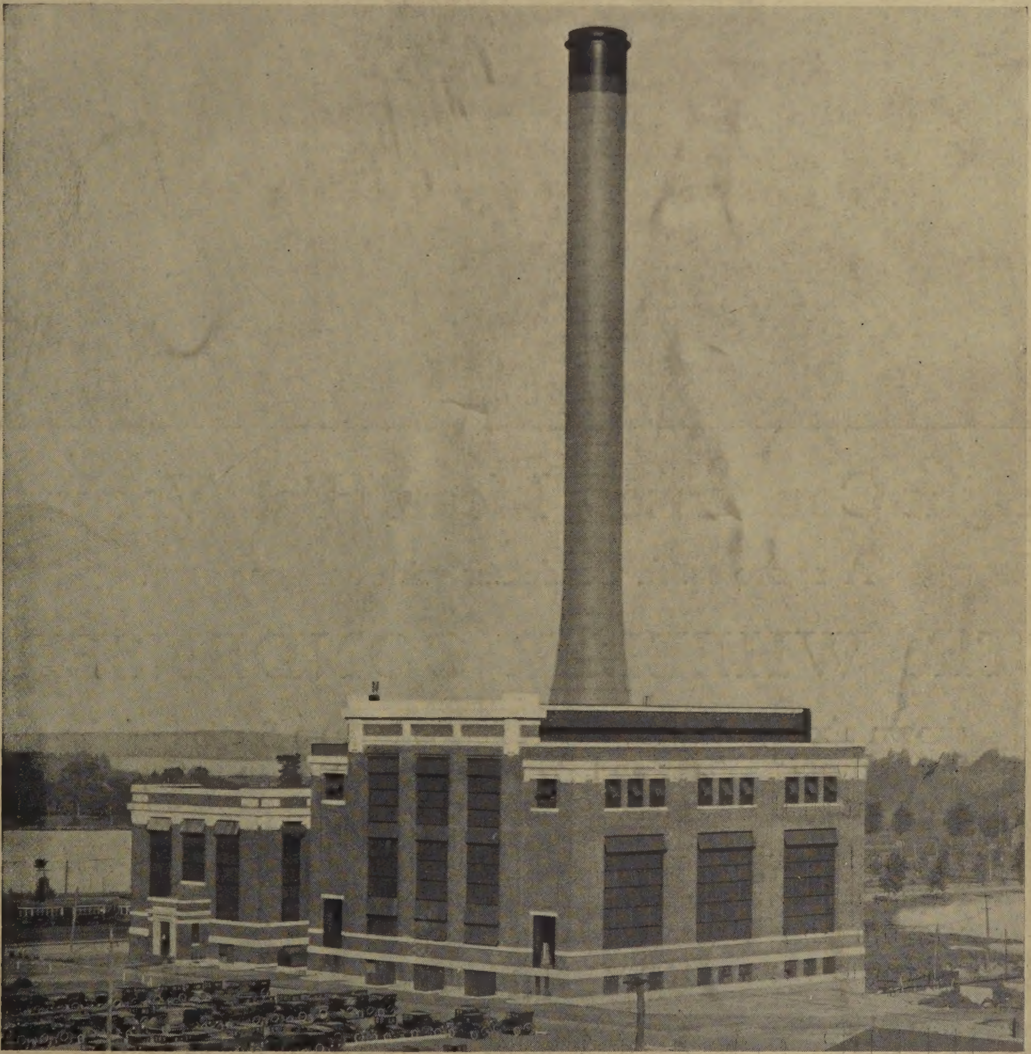
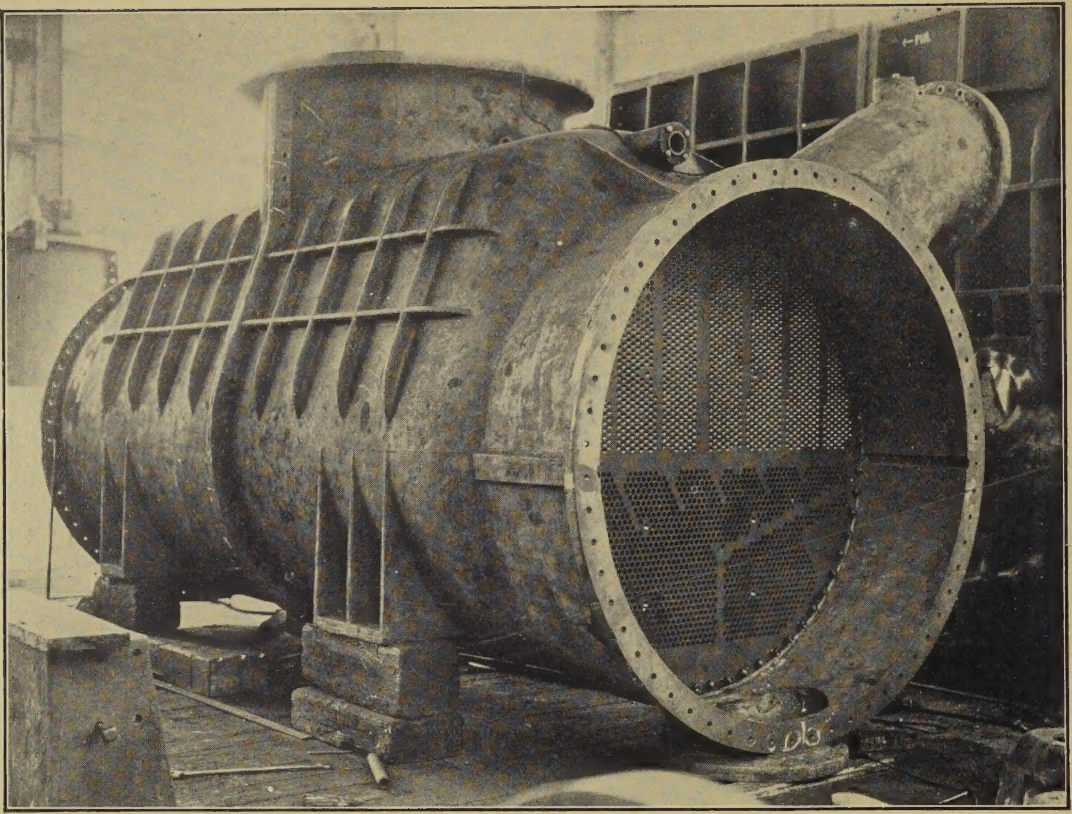


AN INDUSTRIAL POWER PLANT CAPABLE OF PRODUCING HALF A MILLION POUNDS OF STEAM PER HOUR

Steam for Industrial Processes and Factory Heating may be needed in far greater volume than for electric power generation. This new station at the Erie Works of the General Electric Co. supplies all these needs in proper proportion. (*See p. 312*)

In This Issue:

Electrification Railroads
Dielectric Strength
Construction Finance
Industrial Power Plant
Ballast Resistor
Crystal Structure
"K-m" Chart
Windage in Gases
Ferro-Magnetic Theory
Paralleling 25,000 Cycles
Two-speed Synchronous Motor



Tight Condensers Mean High Vacuum

A 13,000 sq. ft. Condenser with only one joint.

The WHEELER CONDENSER

shown above, built for the Holtwood Steam Station of the Pennsylvania Water and Power Co., is made in two pieces with integral cast-on water boxes.

A condenser with few joints is easier to keep tight and requires less attention. A tight condenser means higher vacuum and higher condensate temperature in comparison with the vacuum temperature.

WHEELER CONDENSER & ENGINEERING CO.
149 Broadway, New York
Works - CARTERET, N.J., NEWBURGH, N.Y.

EXPENDED FOR GROWING UTILITIES

$100,000,000 a Year Backed by Stone & Webster Experience

Pioneers for 35 Years

PUBLIC UTILITIES are successfully meeting a huge and fast-growing demand for electric light, power and transportation. Practically as old as the industry itself, the Stone & Webster organization has kept even pace with the extraordinary expansion of the utilities for thirty-five years.

Expenditures $100,000,000 Yearly

Over $100,000,000 yearly is expended through the Stone & Webster organization for public utilities construction, maintenance and operation. These activities extend into nearly every important state. The home office directing the financing, construction and operation of properties numbers 1500 people and occupies three acres of offices.

Operating Managers for 60 Companies

Stone & Webster provides operating management for sixty separate public utility corporations. The record of these properties is an accurate measure of Stone & Webster operating, engineering and financial skill.

During the war the strength and soundness of the utilities was severely tested. The Stone & Webster companies achieved notable results in maintaining both their physical condition and their record of dividends.

The Charles A. Coffin Medal—awarded to the company contributing most to the development of electric transportation—was won last year by a Stone & Webster property.

Stone & Webster service is in demand the country over. These facts show its value.

Construction 2¼ Million Horse Power

Reports on $5,500,000,000

Stone & Webster has examined and appraised properties to the total value of five and one-half billion dollars, including many of the country's foremost public utilities.

Its construction of power stations aggregates 2,250,000 horse power. The systems fed wholly or in part by these stations serve a population of 15,000,000—twice the population of New England. This includes 7,000,000 served by systems receiving power from Stone & Webster-built hydroelectric plants.

Power construction work in progress is a half million horse power. Three-quarters is for old customers who have learned that Stone & Webster-built stations pay dividends. This is because of the economy for which they are famous, and also because Stone & Webster knowledge based on actual experience of operating sixty widely-distributed utilities is available for extending old systems or planning new ones.

For Investors

The Securities Division of Stone & Webster rounds out and completes the organization's intimate contact with the public utilities industry. Through its operations in financing properties and handling their securities it provides thousands of individuals and institutions with favorable opportunities to invest their funds in electric light, power and transportation—fundamental necessities of modern life.

STONE & WEBSTER

INCORPORATED

DESIGN · BUILD
OPERATE
FINANCE

NEW YORK: 120 Broadway
SAN FRANCISCO: Holbrook Bldg.

BOSTON: 147 Milk Street

CHICAGO: 38 South Dearborn Street
PHILADELPHIA: Real Estate Trust Bldg.

I. P. Morris Department

The Wm. Cramp & Sons Ship & Engine Building Co.

Richmond and Morris Sts., Philadelphia

NEW YORK OFFICE—100 BROADWAY **BIRMINGHAM OFFICE—AMERICAN TRUST BUILDING**

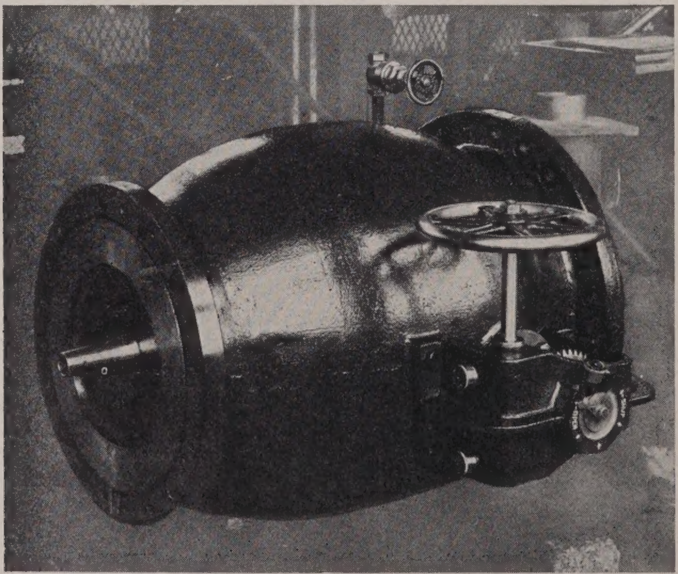
Designers and Builders of

JOHNSON HYDRAULIC VALVES

Valves of the Johnson type have been constructed in sizes ranging from 5 inches to 21 feet Inlet diameter

These Valves are particularly adapted to the following uses:

HYDRAULIC TURBINE PENSTOCKS
PRESSURE PIPE LINES
HIGH PRESSURE FIRE SERVICE
AUTOMATIC REGULATION OF FLOW FROM RESERVOIRS
THROTTLING AND FREE DISCHARGE FROM HIGH TO LOW PRESSURE CITY WATER WORKS SYSTEMS



18-inch Johnson Valve built for the Southern Sierras Power Company and designed for free discharge into the atmosphere under a head of 400 feet

Special Johnson Valve Features

Simplicity of Operation
Strength of Design
Combination Stop and Check Valve Characteristic
Tightness against Leakage when Closed
Automatic Closure in Emergencies
Durability and Dependability

Write for Johnson Valve Bulletin No. 3

ASSOCIATED COMPANIES

THE PELTON WATER WHEEL CO., San Francisco and New York
DOMINION ENGINEERING WORKS, LTD., Montreal, Canadian Licensees
SOCIEDADE ANONYMA, HILPERT, Rio de Janeiro, Brazilian Licensees

ELLIOTT POWER PLANT EQUIPMENT

ELLIOTT POWER PLANT EQUIPMENT

Special Heaters

RECENTLY Elliott Company has built Open Feed Water Heaters of special construction for several of the most modern and efficient central stations. These Heaters have been designed and proportioned along precisely the same lines as Class "E" Heaters, but in view of the service involved, have been constructed of special material. The occasion for the special construction was the use of exhaust steam derived from small turbines, which was highly superheated, and imposed temperature stresses beyond the limits of satisfactory cast iron construction.

These Heaters were constructed of welded and riveted ingot iron shells, all joints, seams and rivet heads being electrically welded. End heads were of cast steel, to provide rigidity. Steam inlets were fixed to the cast steel heads to provide resistance against pipe expansion stresses. Interior pan racks were of open hearth steel, and the tray pans, of similar design to Class "E" trays, were of malleable iron, to eliminate breakage. Floats were located in external float boxes, and float valves, of the balanced type, were of the highest grade construction. Provisions similar to those used in the Class "E" were employed to eliminate water hammer.

Ingot iron was selected as the most suitable material, since it had the endurance of steel under recurring temperature stresses, and as nearly as possible in commercial materials, the corrosion immunity of cast iron. Welding was employed to make a permanently tight structure. Riveting was based upon considerations of strength. The plate thickness was ¼ inch minimum and greater for pressures higher than atmospheric. These Heaters can be provided for any safe operating pressures.

In operation, the surfaces of these Heaters could be expected to be alternately blasted with highly superheated steam and wetted with water. While the heat content of the superheat was small, it introduced the problem of very high temperatures and extremely sudden temperature change. The service was as severe as it is possible to encounter in almost any type of apparatus, i. e., sudden and violent changes of temperature. The construction, the selection of material and the design have been adequate for the purpose contemplated.

This design can be built to any capacity and any pressure standard which is required. Generally, however, it is unsafe, from an operating standpoint, to use Open Heaters at high pressures.

ELLIOTT POWER PLANT EQUIPM

Feed-Water Heaters

Bulletin D-1 January, 1925

ELLIOTT COMPANY
PITTSBURGH, PA.
General Sales Offices: · Jeannette, Pa

Whatever your Feed Water Heater Needs

Elliott Company is building the widest variety of heating equipment. Elliott Company engineers are competent to adapt this apparatus to the best uses of the purchaser, and our resources are always available for giving to prospective purchasers frank analysis of the adaptability of various pieces and types of equipment and for suggesting possible advantageous combinations for specific purposes.

The new bulletin on Elliott Feed Water Heaters, pages from which are reproduced above, shows the breadth of Elliott facilities for producing Feed Water Heaters of all types and to fit any conditions.

A copy of the bulletin will give you a good idea of what we have to offer. We believe you will find this bulletin of interest and well worth asking for.

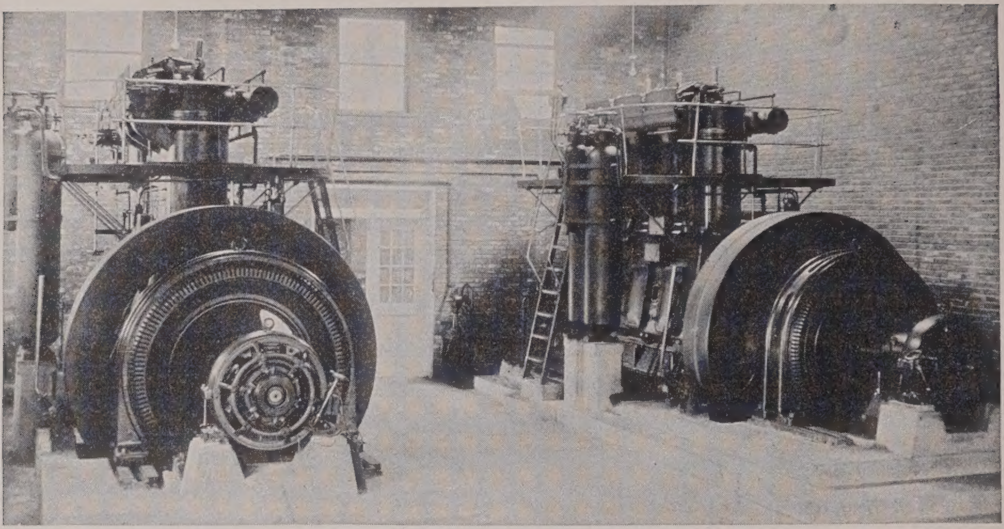
ELLIOTT
Feed Water Heaters—all types

ELLIOTT COMPANY

GENERAL SALES OFFICES AND WORKS
JEANNETTE, PA.
DISTRICT OFFICES: ATLANTA, BALTIMORE, BOSTON, CHICAGO, CINCINNATI, DETROIT, CLEVELAND, NEW YORK, KANSAS CITY, PHILADELPHIA, PITTSBURG, ST. LOUIS, SYRACUSE

EXECUTIVE OFFICE—PITTSBURGH, PA.
PRODUCTS
CONDENSERS, AIR EJECTORS, FILTERS, DEAERATORS, STRAINERS, SEPARATORS, GREASE EXTRACTORS, AUTOMATIC VALVES, BLOW-OFF VALVES, HEATERS

D-160



Three types of power units were scrapped here because they could not equal Diesel Engines

These two 285-b.h.p. McIntosh & Seymour Diesel Engines drive 240-kv-a. alternators with direct connected exciters. The load factor is high, due to heavy current demand from waterworks, flour mills, and grain elevators, in addition to the usual lighting and small power demands.

The station in which they are located has been converted successfully from a plain non-condensing steam plant to a producer gas plant and then to a high-grade modern condensing steam plant. On final installation of Diesel power, the old steam apparatus was kept in reserve for some time, but has since been dismantled.

These Diesel Engines have now proven themselves decidedly superior to any other prime movers that could have been used here, and they have further made profitable an additional load that could not possibly pay with a less efficient plant.

The recent installation of a third and larger (500-b.h.p.) McIntosh & Seymour Diesel confirms these statements.

Diesel Engine power can be installed in units as business increases, and with this procedure the total power cost is practically no greater than when taking all the power from one large unit.

Our Engineers are prepared to explain this unique feature and to tell you exactly what economies Diesel power would effect in your own plant, if you will tell us your present operating conditions.

At least write for literature.

McINTOSH & SEYMOUR
CORPORATION
Main Offices and Works: AUBURN, NEW YORK

SALES OFFICES:

New York City
149 Broadway

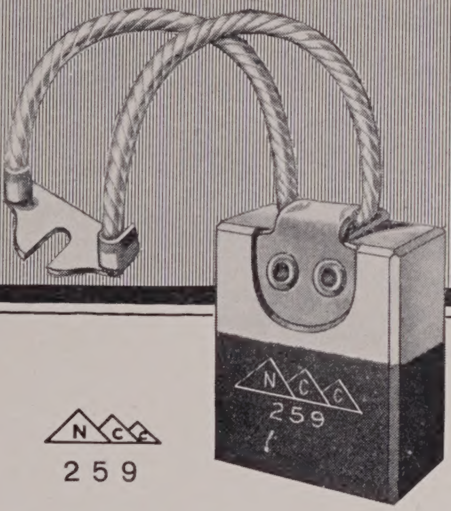
Kansas City, Mo.
1016 Baltimore Ave.

Jacksonville, Fla.
412 Bisbee Bldg.

Houston, Texas
317 Humble Bldg.

San Francisco
815 Sheldon Bldg.

McINTOSH & SEYMOUR
DIESEL ENGINES



NCC
259

UNIFORMITY. Brushes used in DC motors and generators and on the DC side of rotary converters must be uniform in order to ensure successful operation. Such uniformity is a marked characteristic of NCC Grade 259.

To make this uniformity a guaranteed certainty, the Union Carbide and Carbon Research Laboratories, Inc., developed control specifications for the manufacture, testing and inspection of National Grade 259, which have constantly been maintained in our factories.

Unswerving vigilance is exercised to maintain this high degree of control. Infinite pains in testing materials, unceasing attention to manufacturing processes, and most complete determination of the characteristics of the product, guarantee its uniformity. We will welcome an opportunity of demonstrating to you the remarkable qualities of this grade. Its uniformity has been thoroughly proved in service.

National
Pyramid Brushes

Manufactured and guaranteed by

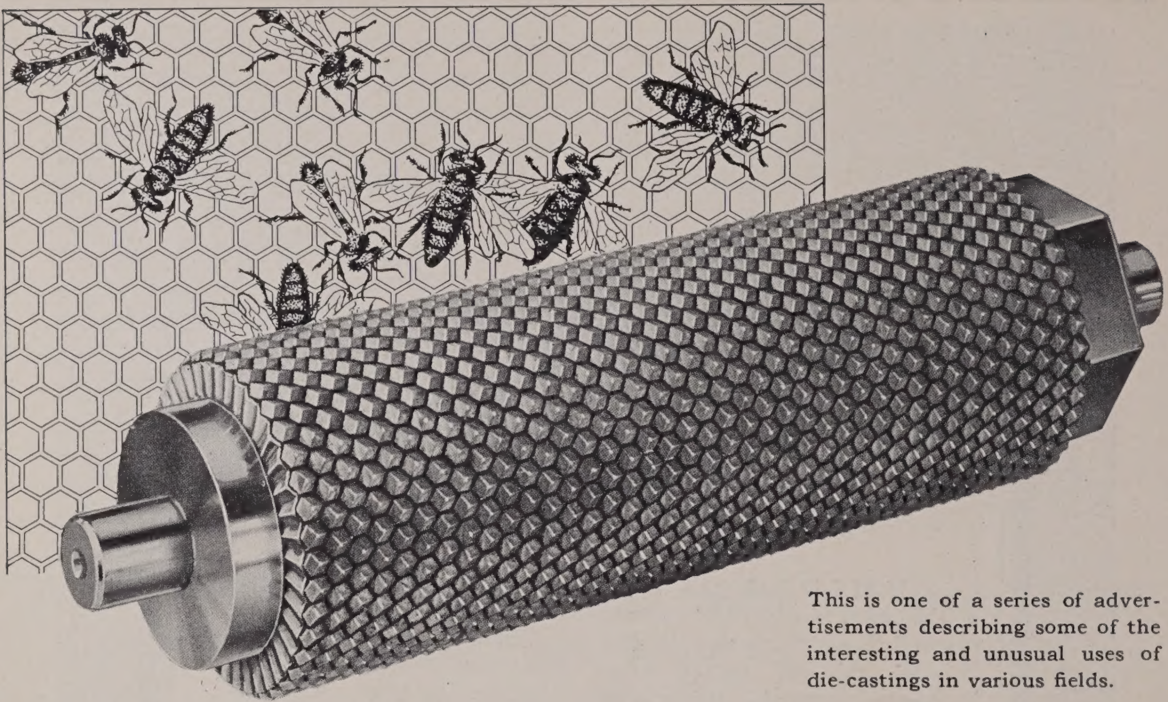
NATIONAL CARBON CO., INC.
Cleveland, Ohio San Francisco, Cal.
Carbon Sales Division
Canadian National Carbon Co., Limited, Toronto, Ontario

Emergency Service Plants

CHICAGO, ILL.:
551 West Monroe St.
Phone: STAte 6092

PITTSBURGH, PA.:
7th Floor, Arrott Power Bldg.
No. 3, Barker Place
Phone: ATLantic 3570

NEW YORK, N. Y.:
357 W. 36th St.
Phone: LACkawana 8153



This is one of a series of advertisements describing some of the interesting and unusual uses of die-castings in various fields.

Speeding up the output of the busy bee

THE foundation of every honeycomb is a wax wall filled on both sides with recesses, the edges of which extended outward form the familiar hexagonal cells. Time was when bees spent many of their working hours constructing this comb foundation. Today it is produced mechanically by running a sheet of wax between die-cast rollers similar to the one pictured. Thus bees have more time to devote to the production of honey.

The use of die-castings in this case not only speeds up the honey output but results in time-saving in the production of the machine of which the rollers are a part. Similarly die-castings are being utilized by many manufacturers to speed up production and effect economies in the manufacturing of their products. Die-cast parts minimize machining operations (sometimes eliminate them entirely), reduce assembling costs and cut factory overhead.

We are making aluminum, zinc, lead and tin die-castings for a wide range of industries. Our expert staff of designers, die-makers, and metallurgists insures die-castings of proper design, accurate dimensions, required solidity and fine finish. Moreover, our large facilities place us in a position to handle all orders economically and with promptness. Your inquiries are solicited.

When you buy die-castings from us, you are assured of the same high quality that has established our Dutch Boy trademark as a mark of excellence on babbitts, solder and paint materials.

NATIONAL LEAD COMPANY

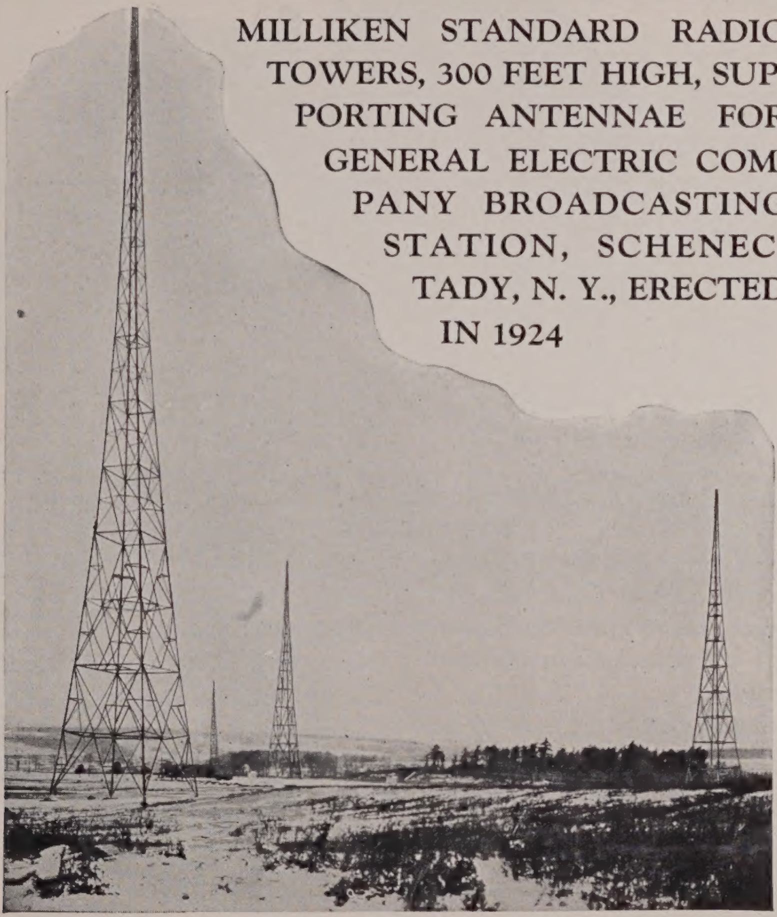
111 Broadway Die-Casting Division New York, N. Y.

Western Representatives: E. R. McCormick, 2599 Cadillac Ave., Detroit, Mich. A. H. Bergedick, 667 Bowen Street, Dayton, Ohio. A. A. Gildemeister, 444 4th Street, Toledo, Ohio.

ALUMINUM, ZINC, LEAD *and* TIN

DIE-CASTINGS

Say you saw it advertised in the GENERAL ELECTRIC REVIEW



MILLIKEN STANDARD RADIO TOWERS, 300 FEET HIGH, SUPPORTING ANTENNAE FOR GENERAL ELECTRIC COMPANY BROADCASTING STATION, SCHENECTADY, N. Y., ERECTED IN 1924

MILLIKEN Standard Radio Towers, 300 feet high, are being used by the General Electric Company at its new experimental broadcasting station, Schenectady. These towers were selected by the leading broadcasting station in the world for stability, reliability, long life and economy, to secure the best results in long distance service.

The General Electric Company leads in all electrical development and specialized broadcasting equipment. This station represents the last word in experimental broadcasting.

MILLIKEN Standard Radio Towers are hot galvanized throughout. They are carried in stock for immediate shipment and are furnished in heights ranging from 66 feet to 300 feet.

Milliken towers are used also at such important broadcasting stations as—

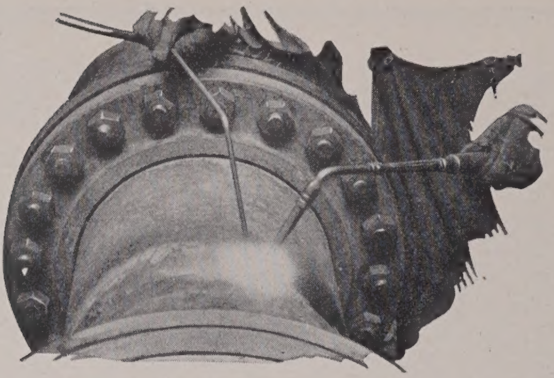
WPG —Municipal Station, Atlantic City, N. J.
WEAF—American Telephone and Telegraph Co., New York
WSAI —United States Playing Card Co., Cincinnati
WEEI —Edison Electric Illuminating Co., Boston
WBZ —Westinghouse Electric & Mfg. Co., Springfield, Mass.
WHAZ —Rensselaer Polytechnic Institute, Troy, N. Y.
WMAF—Round Hills Radio Corporation, Dartmouth, Mass.
WCX —Detroit Edison Co., Detroit
WGBS —Gimbel Brothers, New York
WAHG—A. H. Grebe Co., Brooklyn, N. Y.

Catalogs in English and Spanish will be furnished on request.

MILLIKEN BROTHERS MFG. CO., Inc.

2341 Woolworth Building - - - - New York, N. Y.

Also, Manufacturers of Transmission Towers and MILLIKEN BUILDINGS



The *purest iron* makes the quickest, most dependable weld

Welding men have found that Page Welding Wire and Electrodes made from commercially pure Armco Ingot Iron, flow more freely and assure the most uniform deposit of dense, clean metal.

Result: Reduction of labor cost per job to a minimum—and better welds.

Armco Iron for Welding Wire is the recognized standard—guaranteed 99.84% pure. Page Electrodes and Welding Wire conform to A. W. S. specifications. Their cost is so small in comparison to the results obtained, it always pays to insist on their use.

PAGE

WELDING WIRE and ELECTRODES

PAGE HIGH CARBON

Gas Welding Wire and Electrodes

The harder the welding job, the more important the welding material. For high-carbon steel welding use Page High Carbon Wire and Electrodes—save welding time and insure the success of the weld.

Hardness tests indicate that surfaces welded with Page High Carbon Steel have wearing qualities fully equal to those of the base metal.

To identify Page High Carbon Wire and Electrodes—look for the red tag.

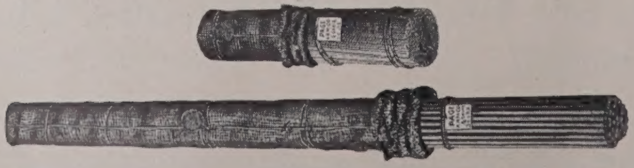
PAGE STEEL & WIRE COMPANY

Bridgeport, Connecticut

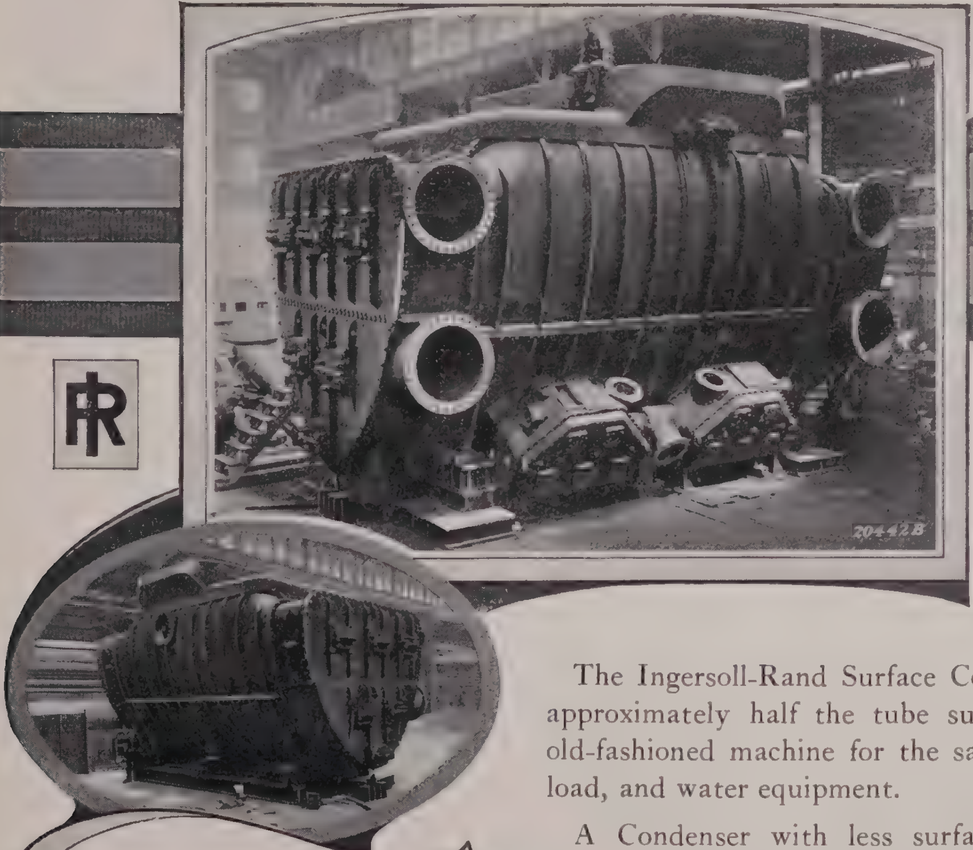
District Sales Offices: Chicago, New York, Pittsburgh, San Francisco
An Associate Company of American Chain Co., Inc., of Bridgeport, Conn.

STEEL AND WIRE PAGE QUALITY PRODUCTS

AMERICAN TRADE MARK ARMCO REG. U.S. PAT. OFF. INGOT IRON



A Condenser With Less Surface Is Worth More



The marked reduction in the tube surface of the Ingersoll-Rand Surface Condenser is accomplished by the careful co-ordination of many new features.

The result is not obtained by any single feature no more than turbine design is completely solved by some single feature. There are many years of experiment and research back of I-R design, followed by four years of actual commercial operation and experience.

The Ingersoll-Rand Surface Condenser has approximately half the tube surface of the old-fashioned machine for the same vacuum, load, and water equipment.

A Condenser with less surface is worth more. It affords lower operating and maintenance costs because there are fewer tubes to inspect, maintain and replace when corroded. Leakage and time for cleaning are reduced to a minimum.

It will pay you to investigate the features which characterize Ingersoll-Rand Surface Condenser design.

Bulletin 9036 on request.

INGERSOLL-RAND COMPANY—11 BROADWAY, NEW YORK CITY

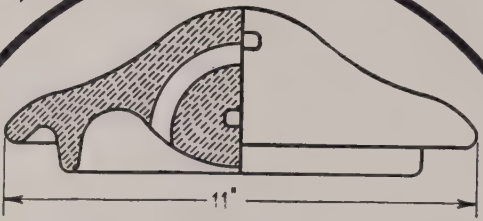
Offices in principal cities the world over

For Canada: Refer, Canadian Ingersoll-Rand Co., Ltd., 260 St. James St., Montreal, Quebec.

Ingersoll-Rand

Say you saw it advertised in the General Electric Review

The New Hewlett



All the mechanical and electrical values of the cemented type

THIS is a close-up of the new Locke Hewlett as near as we can bring it to you in this space, and still have room to tell you of the outstanding advantages it possesses over the previous Hewlett design—itself good and in great favor since 1901.

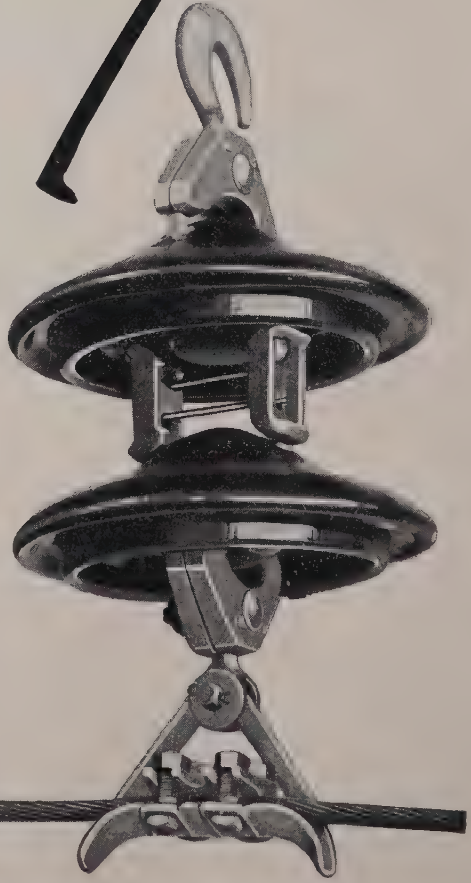
But this new Locke Hewlett will stand the closest kind of inspection—under the most rigid mechanical and electrical tests, and frequent flashover. It is unreservedly the equal of the cemented types in strength. While retaining all of the desirable features of the original Hewlett insulator, this new design embodies many improvements.

Here are some of them:

1. Improved methods of manufacture permit the use of dense porcelain—the time-tested Locke porcelain — famous for thirty years.
2. Approximately an inch of porcelain between links.
3. Improved flexible coupling.
4. Rectangular holes, giving greater bearing surface, and greater unit strength.
5. All hardware made from drop-forged steel.
6. Indestructible zinc-armored pad, with asbestos steam packing, between link and porcelain.
7. Positive nut lock.
9. Simple, inter-connecting hardware.
9. Changed contour — giving better drainage, improved distribution of electrical stress, and more pleasing appearance.
10. All the mechanical and electrical values of the cemented type.

Seeing is believing. We will be glad to supply samples for test and to afford an opportunity for investigation of our manufacturing methods, and further details of construction of this new Locke Hewlett design.

LOCKE INSULATOR CORPORATION
BALTIMORE, MARYLAND
Factories: Victor, N. Y., and Baltimore, Md.



The new Locke catalog, 254 pages, stiff cloth binding, is ready for distribution to consulting engineers and operating company officials. Send for your copy without delay.

LOCKE
PORCELAIN

Anaconda Service is complete

Whether the call be for Sheets, Wire, Rods, Tubes or Special Wrought, Drawn or Extruded Shapes, in Copper, Brass or Nickel Silver, The American Brass Company supplies the best. 100 years of practical experience have led to the development of processes and methods which are unexcelled.

Seven Mills, advantageously located near the large consuming centers, assure prompt deliveries, at lowest shipping costs.

This complete service eliminates the necessity of coordinating separate deliveries.

Use all Anaconda Products—the standard of the Copper and Brass Industry.

ANACONDA
from mine to consumer

Anaconda Products include

CONDENSER TUBES
TURBINE BLADING
BUS BARS and TUBES
COPPER WIRE and CABLE
Bare and Insulated
COMMUTATOR SEGMENTS
WELDING RODS

THE AMERICAN BRASS COMPANY

GENERAL OFFICES: WATERBURY, CONNECTICUT

New York, Chicago, Boston
Philadelphia, Providence, Pittsburgh
Cleveland, Detroit, Cincinnati
St. Louis, New Orleans, San Francisco

ANACONDA
from mine to consumer

Mills and Factories:
Ansonia, Conn., Torrington, Conn.
Waterbury, Conn., Buffalo, N. Y.
Hastings-on-Hudson, N.Y., Kenosha, Wis.

In Canada: ANACONDA AMERICAN BRASS LIMITED, NEW TORONTO, ONTARIO

from locomotive to fan the right brush for every need

And while there is a vast difference between a Stackpole Carbon Brush on a locomotive and on an electric fan, yet they both have a common characteristic—uniformity in composition.

The exceptionally long life of Stackpole Brushes and their efficient functioning under all stresses will make you a permanent user.

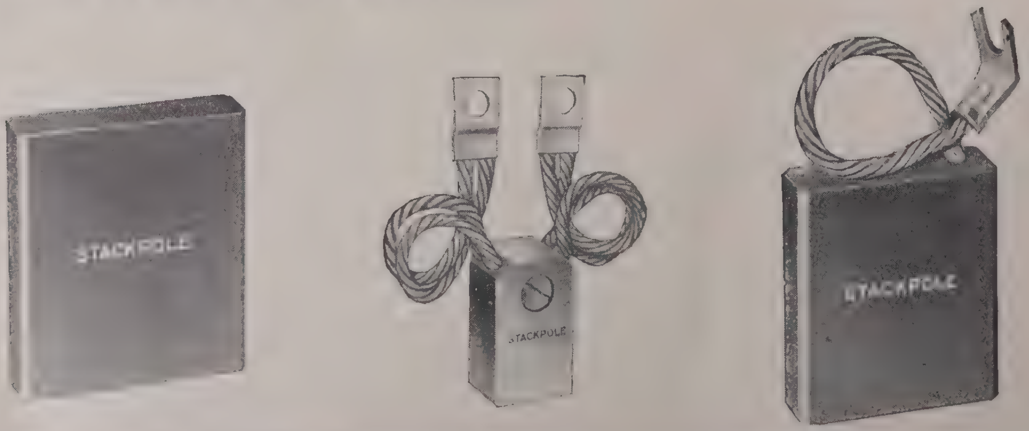
Chattering, high mica, heating, flat spots—Stackpole Carbon Brushes eliminate them all.

Stackpole carbon brushes

Let us send our Catalog No. 8

Stackpole Carbon Company

St. Marys, Penna.



The triple-guaranteed expansion joint

GUARANTEED

[1] To compress one quarter inch axially when subject to a compressive force of 125 pounds per inch nominal diameter of pipe.

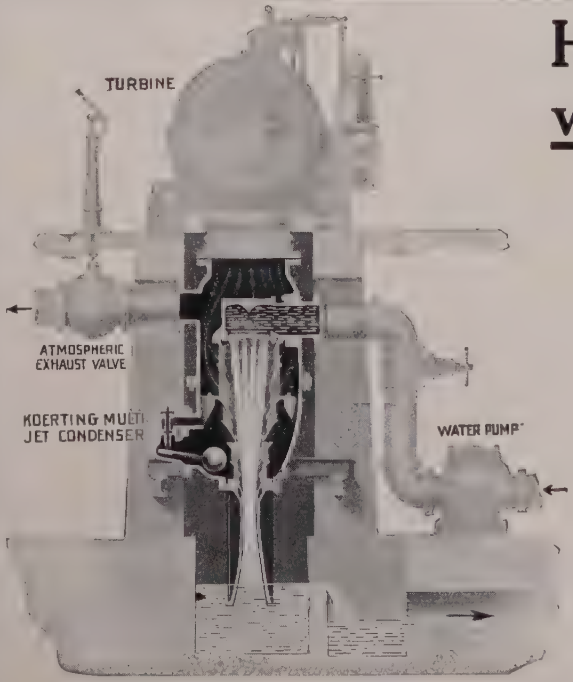
[2] To expand one quarter inch axially when subject to an expansive force of 150 pounds per inch nominal diameter of pipe.

[3] To distort laterally one eighth inch with a force of 125 pounds per inch nominal diameter of pipe.

Send the Coupon

Name ....
Address ....
The Griscom-Russell Company,
2140 West Street Bldg., New York.
Gentlemen:
Please send us a copy of Information Leaflet 178 on G-R Expansion Joint.
GER 5-25

THE GRISCOM-RUSSELL COMPANY
2140 West St. Building, New York
BRANCHES IN PRINCIPAL CITIES



High Vacuum without Air Pumps

Steam turbines and engines can be operated under continuous high vacuum when connected to

SCHUTTE KOERTING

Multi-Jet Condensers

The water jets condense the steam and remove the air.

Built in 40 sizes—100 kw. to 15,000 kw.

Ask Condenser Dept. for Bulletin 5-A.

Visit our booths (50 & 51) at the Milwaukee Power Show

SCHUTTE & KOERTING CO., 1196 Thompson Street, Philadelphia, Pa.

B T-H Electrical Equipment

Steam Turbines
Turbo-Generators
Turbo-Alternators
Power Station Switchgear
Rotary Converters
Sub-Station Switchgear
Industrial Motors
Industrial Switchgear
Electric Locomotives

This Company manufactures electrical equipment for every service, ranging from the smallest lamp to the largest electrical machinery manufactured in the United Kingdom.

The British Thomson-Houston Co., Ltd.
Electrical Engineers and Manufacturers
Head Office: Rugby, England **London Office: "Crown House," Aldwych**

Investment Bankers
are offered
Power and Light Securities

issued by companies with long records of substantial earnings.

We extend the facilities of our organization to those desiring detailed information or reports on any of the companies with which we are identified.

Electric Bond and Share Company
(Paid-up Capital and Surplus $70,000,000)
71 Broadway - - - New York

Buffalo stoker fan at the Municipal Power Plant
Fort Wayne, Ind.

Municipal power plants use many "Buffalo" Stoker Fans

Municipal power plants frequently find that the best way to obtain economical power is to install reliable modern apparatus and put a competent engineer in charge of it.

Thus we find Buffalo stoker fans in many of these successful plants. Engineers approve of the sturdy, rigid construction of housings and wheels. They know that the patented Buffalo inlet vanes make it impossible to overload motors; that a good efficiency over a wide range of capacity is better than a slightly higher efficiency at the peak of a sharp curve.

They appreciate the high speed character of Buffalo fans which makes them ideal for motor or turbine drive.

If you'd like to know more about the advantageous features of Buffalo stoker fans, send for our new mechanical draft catalog No. 730. It tells the whole story.

Buffalo Forge Company
170 Mortimer Street Buffalo, N. Y.
Branches in all principal cities.

KEYSTONE
GREASE
The Master Lubricant

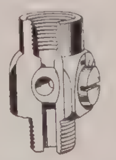
Paid for in a year, *or less*

RECORDS show, after a careful investigation, that an investment in the KEYSTONE SAFETY SYSTEM of KEYSTONE GREASE LUBRICATION is returned within six months to a year.

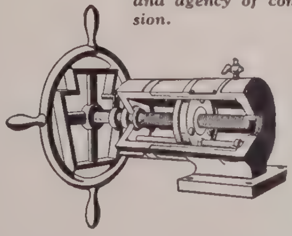
Such has been the experience of leading industrial executives who have equipped ore bridges, open-hearth cranes, belt conveyors, and various types of machinery in steel, paper, wood-working, rubber and cement mills; besides other miscellaneous machines—crushers, boring mills, presses, lathes, etc., with the Keystone Safety System of Keystone Grease Lubrication. Get all the details. Write!

KEYSTONE LUBRICATING CO.
Est. 1884
PHILADELPHIA, PA.
at 21st and Clearfield Streets

Sectional view below of lubricator, which is the main grease reservoir and agency of compression.



Above is sectional view of Pressure Reduction Valve placed at each bearing.



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GERARD SWOPE
President, General Electric Company
A recent address by Mr. Swope appears on p. 284

GENERAL ELECTRIC REVIEW

THE DETERMINATION OF THE INDUCTIVE RELATION BETWEEN POWER AND COMMUNICATION CIRCUITS

Where space is limited, and power circuits and communication circuits are in close proximity, there may be a voltage of considerable magnitude induced in the communication circuits. Other undesirable effects may also be noted. Some of them occur even in normal service on the power system, such as induced voltage from the telephone conductors to ground caused by their position in the electrostatic field between the power lines and ground, and ground currents due to unbalanced line capacitance, such currents creating noise in the communication circuits.

In the United States this relationship between power circuits and communication circuits has been made the subject of an investigation by the Inductive Interference Committee of the California Railroad Commission, the results of which appeared in the report of that committee dated April, 1919. More recently, Mr. George A. Campbell published a paper on "The Mutual Impedance of Grounded Circuits" in the *Bell System Technical Journal* of October, 1923.

At the present time, a systematic and resolute study of all the problems concerned is being made by a joint committee of the National Electric Light Association, the American Telephone and Telegraph Company, and representatives of the electrical manufacturers. Some of the matters under consideration are the measurement and effect of residual voltages and currents, the wave form of generators, the relation between the telephone interference factor and noise, the harmonics due to the permeability of the steel in transformers, etc. Supplementing these phases of research work, actual tests are being conducted on various power systems. In this connection it is to be noted that the prevailing practice in this country of solidly grounding the system neutral makes possible the use of protecting equipment so sensitive as to prevent long-continued, heavy, short-circuit currents and hence no voltages of great magnitude are induced in the neighboring communication circuits.

In Japan, the Government controls the communication circuits and also regulates the power companies. In the conduct of this joint supervision, certain of the regulations adopted to prevent interference between the two classes of circuits have placed a handicap on the technical development of the power companies. One of these requirements is the grounding of the transformer high-tension neutrals through a high resistance, i.e., of the order of 500 to 800 ohms. This renders difficult the successful application of sectionalizing relays to the transmission line, with the result that short-circuit currents may flow for considerable periods of time.

The Electrotechnical Laboratory of the Department of Communications, of Japan, has been making a serious study of matters pertaining to interference. Dr. R. Mitsuda, Director of the Laboratory, and his assistant Mr. K. Kasai, have developed a chart for the computation of the electromagnetic induction between power lines and neighboring circuits and it is applicable even though the circuits are not parallel to each other. Through the use of this "K-m" chart the intricate and laborious mathematical operations in calculating such problems are avoided, as explained in the article on page 290. W. W. L.

Electrification of Railroads

By Gerard Swope
President, General Electric Company

An address delivered before the annual meeting of the American Institute of Electrical Engineers, Engineers' Societies Building, New York City, May 15, 1925.—Editor.

One of the most important factors in making this country one and undivided, and tending toward greater solidarity in interest and thought has been the widespread development of transportation. This country is tremendously indebted to the courage and vision of the pioneer railroad builders in welding different sections of the country together, and the union of East and West by solid ties of steel was a magnificent achievement rarely if ever paralleled in the history of any country.

The very existence of our great cities and their growth depends on efficient, expeditious and economical transportation. It is almost impossible to appreciate the amount of transportation involved merely to maintain life in a city like New York. Well informed engineers report that the freight transportation requirements of a city in ton miles have increased 3½ times as fast as its population, and modern city planning is largely a problem for meeting these conditions.

The position that the transportation system in the United States has reached, enjoying as it does the proud distinction of rendering the greatest service to the community as a whole of any in the world, is a monument and credit to the initiative and enterprise of private undertaking.

The part that the steam engine has played in this development is remarkable. Under the inspiration of the engineers associated with the railroads and the manufacturers, the steam engine has met the successive and seemingly insurmountable difficulties presented in moving greater tonnage at higher speeds. Our extensive transportation system has been so admirably served by the steam locomotive that we should not look for a change to another type of motive power unless there are some good and sufficient reasons for its adoption. The steam locomotive will undoubtedly continue for many years in the service with which it has been so closely identified for nearly a century. Further improvements may be expected which will increase the power and the fuel economy of steam locomotives, but however much may be accomplished in this direction there still remains the limitation of power imposed by restrictions in size of the locomotive boiler and fire box, and the inherently lower fuel economy in comparison with the modern steam electric power station.

The problem before the railroads and the country is more efficient, more economical, more expeditious methods of handling the great transportation of this country, and serving the people of the farms and cities in the most satisfactory manner. The electrical manufacturers as well as all manufacturers are vitally interested in the solution of this problem. The electrical manufacturer is not advocating electrification of railroads simply in order to sell his electrical apparatus, as this would be a short-sighted policy. The electrical manufacturer as a member of the whole community to be served, and its hundreds of thousands of employees want the transportation system of the United States the best in the world, and the best adapted to meet the nation's requirements of service at the lowest cost. We do believe that electrification will meet these requirements of a large and increasingly larger portion of our railroads more fully than any other change in the transportation system, and a brief résumé of the reasons therefor follows:

First, the conversion of energy from coal to power is at best inefficient, but the most uneconomical and wasteful is the conversion of power on a steam locomotive in comparison with the high efficiency now developed in the large modern electric power stations of the country, and this difference in efficiency is inherent and cannot be modified to a great extent even by the improvements that have been made and are being made in the efficiency of the steam locomotive. The saving of coal per year, if only one-half of the railroad mileage of the United States were electrified, would be approximately 40,000,000 tons, or at the prevailing market price, $120,000,000 per year. This would be a fine contribution to the conservation of our natural resources, would free human labor in the mines and free investment in handling this tonnage, and increase by more than 10 per cent the carrying power of the railroads so electrified, because this part of the present equipment is now used to transport the coal the railroads themselves consume.

Second, the electric locomotive is not restricted in its capacity, as in the case of the steam locomotive, the latter being limited in power by the size of the boiler it can carry. The central station from which the electric locomotive derives its power is stationary and may have a capacity many times in excess of any number of locomotives that may be on the line at the same time. Electrification thus provides greater possibilities for handling heavier traffic more expeditiously under varying conditions of railroad operation, with less human effort and supervision and at a reduced cost.

Third, the contribution to health, comfort and safety by elimination of smoke and dirt in tunnels and city terminals is apparent. The increased money value, by reason of electrification, to the railroads themselves, to the city from increased tax assessments, and to private property owners because of increase in value and consequent increase in rents could have no more striking illustration than is furnished by the district immediately surrounding the magnificent terminals of the Pennsylvania and New York Central railroads in this city.

Fourth, in many instances capital expenditure for betterments on congested mountain grade divisions may be more profitably made for electrification than for the building of tunnels, construction of additional tracks and more steam engine facilities. The electric locomotive combines enormous tractive power with much higher speed which makes it most effective in increasing the carrying capacity of existing tracks. Thus, its introduction postpones indefinitely any necessity for great expenditures that would be needed to give equivalent operating facilities with steam engines on these mountain divisions.

Fifth, records kept over a long period of time show clearly that the cost of maintenance of steam engines is three times that of electric locomotives, hauling the same tonnage, over the same division and under the same operating conditions.

Sixth, for switching and branch line service the Diesel electric locomotive and the gas electric car are available. These consist of a gasoline or Diesel engine driving an electric generator, which in turn drives electric motors. The unit is self-contained and independent of trolley or third rail.

This briefly sets forth the advantages of electrification for railroad service over steam, irrespective of whether alternating current or direct current is utilized. Electrification with either has been of great benefit to the railroads, the traveling public and the community served.

There is still difference of opinion in the minds of prominent engineers as to the relative merits of alternating and direct current to meet the varying conditions of transportation service in the United States. This difference is far less important than the difference between either and steam locomotives.

This difference of opinion exists also in the minds of engineers outside of this country, but in most countries where this problem has arisen it has been met nationally and a national solution arrived at, even in countries where railroads were owned partly by the public and partly by the State. A few examples will be of interest. One system of electrification was adopted for all France, namely, direct current, and the French are proceeding with the work. In England, also, the direct current has been adopted nationally. In Germany and Switzerland alternating current has been adopted nationally. One would naturally expect that the different nations in Europe would differ in their solutions of the same problem because of their traditional differences and diversity of interest. Europe, notwithstanding the tremendous difficulties of the present economic situation, is proceeding more rapidly to solve the problem of electrification of its railroads than we in the United States.

Today, the equipment in the terminals of New York City and Philadelphia are not interchangeable, although both operate under similar conditions in congested areas of great wealth on our Atlantic seaboard. Just as in this country we have a standard gauge for tracks, standard couplers, standard brakes, so as to make our equipment interchangeable, so it is to be hoped that a national electrical standard will be adopted with all its attendant advantages, allowing us to mobilize our resources for the greatest economic development of this country in peace and to protect ourselves most effectively in war.

As the Secretary of Commerce has so clearly pointed out, one common system would save hundreds of millions of dollars in equipment that would otherwise be wasted, and the difficulties, cost and delays of interchange would be greatly decreased.

Standardization will also affect very directly the use of the power developed by the large interconnected public utility companies—so-called super power—and the best utilization of the power developed at the coal mines and waterfalls resulting in the greater use and development of our natural resources.

Electrification is going to call for increased capital outlay, and standardization will materially reduce the amount needed and facilitate the raising of such additional capital:

First, by the greater use of the power developed by the larger central station systems throughout the United States, so that the railroads will obviate the large investment needed for power stations running into millions of dollars, and

Second, by the use, if desired, of car trust certificates or some similar plan to finance the purchase of electric locomotives, which, being interchangeable for all roads, will be much more easily and cheaply financed.

It is to be hoped and much desired that the railroad executives, intrusted as they are with the custody of more than $25,000,000,000 of railroad property, owned by millions of people throughout the United States, and used by many more, will approach this problem from a national and American standpoint, in order to determine the best standard and interchangeable equipment to meet the varying conditions.

Personally I have the greatest confidence that this problem will be solved as the railroad problems in the past have been so ably and patriotically solved. To that end I am happy to pledge the assistance of the great organization with which I am associated, irrespective of individual opinion and solely from the standpoint of national interest. Whatever system is adopted, we stand ready to give the best engineering and manufacturing service that we can render to the railroads of America.

Dielectric-strength-thickness Relation in Fibrous Insulation

F. M. Clark and V. M. Montsinger
General Electric Company, Pittsfield, Mass.

In the March issue of the Review we published an article by Mr. Clark which dealt with the properties of gaseous dielectrics. The present article takes up another, and equally important, phase of the insulation question in that it shows how the measurement of the dielectric strength of cloth and paper may vary under differing conditions of test. In view of the present day impetus toward the manufacture of power cables for higher and higher voltages, the information here offered by the authors should be of particular interest.
—Editor.

Object

The question of the strength-thickness relation in insulation is an important and practical one, because seldom does the dielectric strength increase in proportion to the thickness. Various empirical formulas have been suggested in the literature to show the strength-thickness relation of insulating materials tested in a uniform field. Among these may be mentioned:

The linear relation of Schwaiger⁽¹⁾
The quadratic formula of Steinmetz⁽²⁾
The linear relation between the gradient and the reciprocal of the square root of the thickness as suggested by Peek.⁽³⁾

The experimental data obtained by the writers have led to the indication that a logarithmic relation expressed in the formula $K_v = AT^n$ holds true, where K_v is the breakdown voltage in kilovolts, A the strength per unit thickness, T the thickness, and n a numerical value generally less than unity.

The purpose of the present research was to determine the value of n: first, as a function of the testing methods; second, as a function of the dielectric; and third, as a function of the insulation history, i.e., the drying procedure used, the subsequent treatment, etc.

Two distinct types of dielectric strength tests have been used to determine the value of n in the formula given. The first has been called a "rapidly applied test" and the second a "minute test." By rapidly applied test it is to be understood that the voltage is applied as rapidly as possible to breakdown, beginning with an initial value of approximately 10 per cent of the ultimate puncture voltage. With the so-called minute test, the initial voltage is equal to 40 per cent of the rapidly applied puncture strength. This is followed at one-minute intervals by a potential increase equal to 10 per cent of the rapidly applied strength. In using this procedure, breakdown has been found to occur in from three to five minutes of time.

Discussion

Steinmetz⁽⁴⁾ has said that the dielectric-strength-thickness relationship of solid insulation between parallel plane electrodes is a matter of heat generation and dissipation. With metallic electrodes having comparatively great thermal conductivity, the heat formed in insulation under electric stress is conducted transversely to the terminal. In this case he has shown mathematically that the dielectric strength should vary approximately as the one-half power of the thickness. On the other hand, with electrodes of low heat conductivity such as the

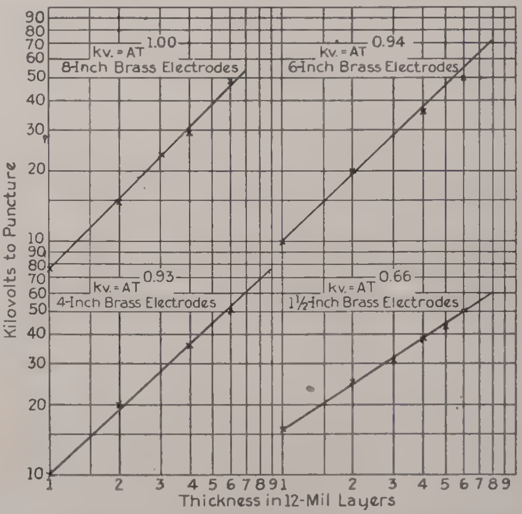

Fig. 1. Effect of electrode size on the strength-thickness relation. Straight-edge brass electrodes with black varnished cloth (0.012 in.) tested in oil at room temperature using 60-cycle alternating current and minute test procedure. All points are averages of 10 tests. All curves run simultaneously

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(1) Schwaiger—Lehrbuch der elektrischen Festigkeit der Isolier-Materialien.
(2) C. P. Steinmetz, A.I.E.E. (1893), page 85.
(3) F. W. Peek, Jr., G. E. Review (1915), page 1050.
(4) Steinmetz, A.I.E.E. (1922), page 299; *Electrical World* (1922), page 866.

impregnated wooden electrodes of K. W. Wagner⁽⁵⁾, the heat generated within the insulation under electric stress is lost more slowly and in a longitudinal direction. This should lead to breakdowns whose values bear an approximately linear relation to the thickness.

Effect of Electrode Size

It has been reported by Farmer⁽⁶⁾ that the average breakdown strength of insulation decreases to a minimum as the electrode testing area is increased. This effect, which has been substantiated, has been found to be accompanied by a change in the strength-thickness relation of the insulation as illustrated in Fig. 1. The points shown are the average of 10 tests made on black varnished cloth in oil at room temperature. The individual tests for the different electrodes upon which the averages are based were obtained alternately upon the same samples of insulation. The dielectric-strength-thickness relation increases with the electrode size from a value $n=0.66$ for 1½-in. electrodes to $n=1.00$ for large-sized terminals above 6 inches. In obtaining these results, especially with the large-sized terminals, particular care was taken to maintain a smooth sine-wave alternating voltage.

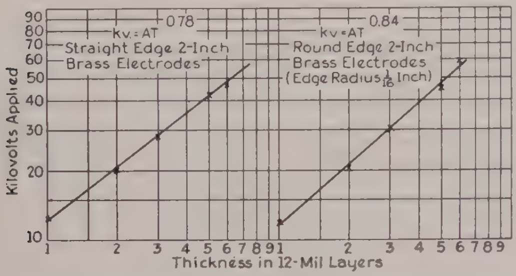


Fig. 2. Comparative edge effects on the strength-thickness relation. Black varnished cloth (0.012 in.) tested in air at room temperature by minute test procedure using 60-cycle alternating current. All points are averages of 10 tests. Both curves run simultaneously

Effect of Electrode Edge Upon the Strength-thickness Relation

No essential difference has been found as between either the breakdown values or the strength-thickness relation existing for straight-edge brass electrodes or brass electrodes whose edges were rounded to a radius $\frac{1}{32}$ of the diameter of the testing surface (Fig. 2). The location of the dielectric failure predominates, however, within the electrode testing area with the use of rounded edge electrodes. This is illustrated in Table I.

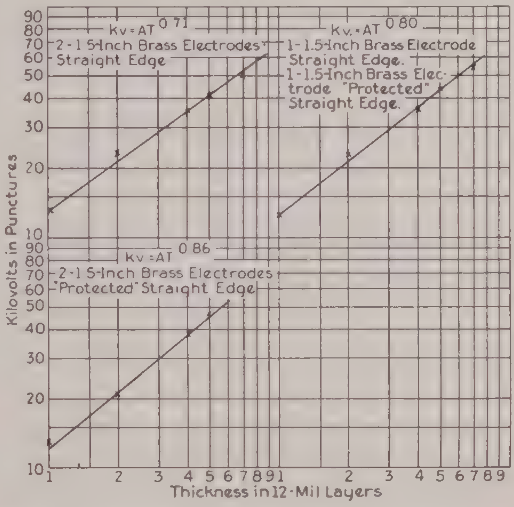


Fig. 3. Edge effect on strength-thickness relation, black varnished cloth (0.012 in.) tested in oil at room temperature using 60-cycle alternating current with minute test procedure. All points are averages of 10 tests. All curves run simultaneously

The strength-thickness relation, however, has been found to be greatly affected by the use of "edge-protected" electrodes. This is illustrated in Fig. 3. In this case, the original minute test relationship between strength and thickness ($n=0.71$), obtained by using 1½-in. straight-edge brass electrodes, has been increased to $n=0.80$ when one of the original electrodes is replaced with a terminal

TABLE I

Minute Tests on Black Varnished Cloth 0.012 in. thick, in Air at Room Temperature

			EDGE PUNCTURES		INSIDE EDGE PUNCTURES	
	No. Trials	Average Breakdown Voltage	No.	Average Breakdown	No.	Average Breakdown
Square edge (5-cm. brass)...............	92	11200	42	11000	50	11300
Edge rounded to ⅛ in. radius (5-cm. brass)	92	11150	32	11300	60	11100

---

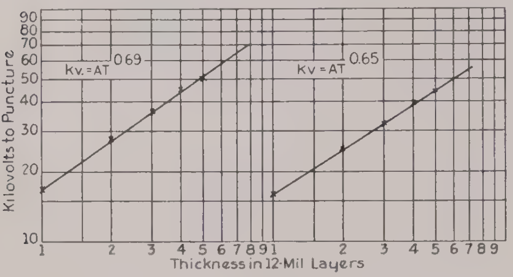
(5) K. W. Wagner, A.I.E.E. (1922), page 1039.

(6) F. M. Farmer, A.I.E.E. 32, page 2193 (1913).

identical in every respect except that the edge has been surrounded by a tight fitting albarene stone collar. When both electrodes were so "protected" the strength-thickness relation was increased to $n = 0.86$.

Effect of Roughened Electrode Surface

Despite the fact that the actual breakdown values of insulation are lowered by the use of a roughened electrode surface (the value of A is changed), no effect has been noted on the value of n. This is illustrated in Fig. 4.



Smooth Rough

Fig. 4. Showing effect of electrode surface condition. Rapidly applied tests in air at room temperature on black varnished cloth (0.012 in.) using 1.5-in. brass electrodes—rough and highly buffed. Both with edges rounded to a radius of $\frac{3}{64}$ in. 60-cycle alternating current used. All points are averages of 10 tests. Both curves run simultaneously

Effect of Varying the Electrode Material

The effect upon the value of n of varying the material of the metallic electrode is negligible. This is illustrated in Fig. 5.

It has been noted that Steinmetz predicted from a mathematical standpoint that electrodes with low heat conductivity would lead to a linear relation between the dielectric strength and thickness. K. W. Wagner⁽⁷⁾ obtaining such a relation with the use of impregnated wooden electrodes suggested that with the use of such terminals each weak point (hot spot) in the insulation was fed independently of the others. Using merely a resistance in series with the insulation, Wagner found that the peculiar effect disappeared due to the fact that, upon hot spot formation, the stored energy in the condenser leaped to the weakened point, resulting in a breakdown lower than that obtained with metallic electrodes. Fig. 6 illustrates the effect obtained using black varnished cloth in air at room temperature. In one case plain impregnated wooden electrodes are used after the manner of K. W. Wagner. In the other case the wooden electrodes are faced with a half-mil sheet of aluminum foil, thus giving the effect of a poor heat conducting electrode inserted in series with a high resistance. Both curves were run simultaneously with practically identical results.

The Comparative Dielectric-strength-thickness Relation of Fibrous Insulation

Using parallel plane electrodes, 1½ in. in diameter whose edges have been rounded to a radius of $\frac{3}{64}$ in., the dependency of strength upon thickness of insulation has been tested for a variety of insulating materials using 60-cycle sine wave alternating voltage at room temperature. The results are shown in the following tabulation:

Case I: Rapidly Applied Tests in Air at Room Temp.

Insulation	Value of (n) Observed Average
Black varnished cloth 0.012 in. (oven-dried at 110 deg. C.)	0.75
Kraft paper (untreated) 0.003 in.	0.92
Linen paper (untreated) 0.0005 in.	1.00

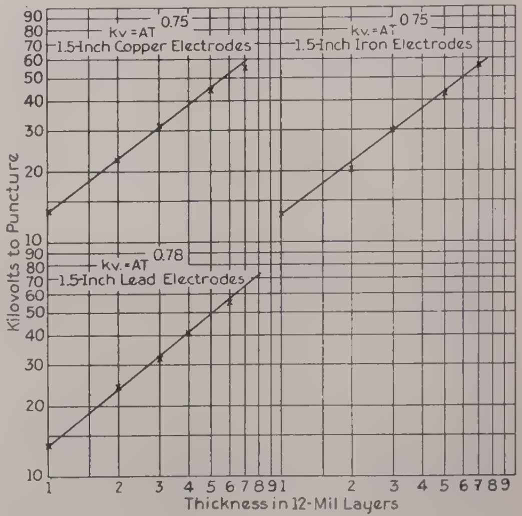


Fig. 5. Effect of metallic electrode materials upon the dielectric strength of black varnished cloth (0.012 in.) tested in oil at room temperature using 60-cycle alternating current with minute test procedure. All points show averages of 10 tests. All curves run simultaneously

Case II: Minute Tests in Air at Room Temp.

Black varnished cloth 0.012 in. (oven-dried at 110 deg. C.)	0.80
Kraft paper (untreated) 0.003 in.	0.92
Linen paper (untreated) 0.0005 in.	1.00

---

(7) K. W. Wagner, Ibid.

Case III: Rapidly Applied Tests in Oil at Room Temp.

Black varnished cloth 0.012 in. (oven-dried at 110 deg. C.)	0.75
Black varnished bond paper 0.005 in. (oven-dried at 110 deg. C.)	0.82
Kraft paper 0.003 in. (vacuum-dried at 115 deg. C.)	0.95
Pressboard $\frac{1}{32}$ in. (vacuum-dried at 115 deg. C.)	0.77
Mica (oven-dried at 115 deg. C.)	0.80

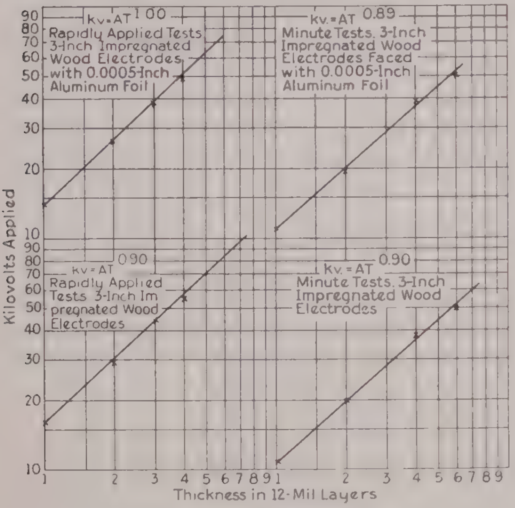


Fig. 6. Strength-thickness relation for black varnished cloth (0.012 in.) tested in air at room temperature by rapidly applied and minute tests using 60-cycle alternating current. Tests made with 3-in. round-edge impregnated wooden electrodes, grain running longitudinally. Case I, electrodes faced with 0.0005 in. aluminum foil. Case II, no aluminum foil used

Case IV: Minute Tests in Oil at Room Temp.

Black varnished cloth 0.012 in. (oven-dried at 110 deg. C.)	0.75
Black varnished bond paper 0.005 in. (oven-dried at 110 deg. C.)	0.75
Kraft paper 0.003 in. (vacuum-dried at 115 deg. C.)	0.75
Linen paper 0.0005 in. (vacuum-dried for 48 hours at 115 deg. C.)	0.80
Pressboard $\frac{1}{32}$ in. (vacuum-dried at 115 deg. C.)	0.67
Mica (oven-dried at 115 deg. C.)	0.69

The Effect of Drying Conditions upon the Dielectric-strength-thickness Relation

It has been found that the procedure used in drying fibrous insulation has considerable effect upon the strength-thickness relation. This is illustrated in the following tabulation:

Electrodes: ½-mil aluminum foil (1½ in. by 2½ in.) held firmly in place between glass plates by spring clips of approximately equal pressure.

Insulation: ½-mil linen paper (2 in. by 3 in.)

Case I.

Treatment	Average Value of n
Soaked in oil at room temperature for 2 weeks	0.81
Soaked in oil at 130 deg. C. for ½ hour	0.84
Heated in air at 110 deg. C. for 96 hours and soaked in oil at room temperature for 2 weeks	0.82

Case II.

Drying Procedure: In all cases the insulation was dried between the electrodes held in place by clamped glass plates. The drying procedure consisted of a 48-hour preliminary air bake and rough vacuum at 115 deg. C. which removed a large part of the moisture. This was followed by a fine vacuum treatment (at less than 500 microns pressure) for varying periods as shown below. The insulation was then slowly oil-impregnated at the temperature of the vacuum treatment and held under cold oil until tested, which usually occurred within 24 to 48 hours.

Treatment	Average Value of n
Heated at 115 deg. C. with vacuum for 48 hours	0.84
Heated at 115 deg. C. with vacuum for 64 hours	0.74
Heated at 115 deg. C. with vacuum for 72 hours	0.53

The Effect of Oil Immersion upon the Value of *n*

No change in the strength-thickness relation has been observed following oil immersion at room temperature up to a period of 77 days. Considerable effect has been noted, however, for oil immersion at higher temperatures.

Linen paper, ½ mil per layer (2 in. by 3 in.), vacuum-dried at 115 deg. C. for 60 hours.

Electrodes, ½-mil aluminum (1½ in. by 2½ in.).

Electrodes and insulation held in place between glass plates by means of spring clamps.

Thickness tested: 3 to 16 layers (1½ to 8 mil).

Original $n = 0.72$ (ave.).

Sealed under oil at room temperature: $n = 0.72$ (ave.) after 77 days.

Soaked under oil in open vessel at room temperature: $n = 0.72$ (ave.) after 77 days.

Soaked under oil in open vessel at 80 deg. C.: $n = 0.50$ (ave.) after 77 days.

The Effect of Voltage upon the Dielectric-strength-thickness Relation

The application of electric stress tends to reduce the strength-thickness relation to a minimum value.

Linen paper—½ mil per layer (2 in. by 3 in.), vacuum-dried at 115 deg. C. for 60 hours.

Electrodes—½-mil aluminum (1½ in. by 2½ in.).

Electrodes and insulation held in place between glass plates by means of spring clamps.

Thickness tested: 2 to 8 mil.

Voltage applied: 3300 volts for time indicated.

Results:

- Original $n=0.72$ ave.
- After 10 days $n=0.56$ ave.
- After 51 days $n=0.52$ ave.
- After 77 days $n=0.515$ ave.

Conclusions

As stated above, the variation of dielectric strength with the thickness of insulation as determined by a-c. voltage tests at room temperature may be expressed by the formula $K_v=AT^n$. The value of n shows itself to be independent of the metallic material of the electrodes or long-continued oil immersion at room temperature, and but little affected by the nature of the voltage application (whether rapidly applied or by minute increments of test voltage). The maximum value is reached for untreated fibrous materials; the effect of varnish or oil treatment being to lower the relationship to a value approaching $n=0.75$ for all insulation. With increasing electrode size or the use of impregnated wooden terminals or metallic electrodes whose edges are protected by a tight fitting albarene stone collar, the strength-thickness relation shows an increase even approaching a linear relation for varnished materials. The value of n, however, is considerably lowered by immersion in hot oil, prolonged exposure to high temperatures during the drying treatment, or the application of long-continued voltage stresses even of relatively low values.

The "K-m" Chart

FOR COMPUTING ELECTROMAGNETIC INDUCTION BETWEEN AN AERIAL LINE AND NEIGHBORING CIRCUITS

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This is a contribution from Japan in which a new method is presented whereby the computation of induced electromotive forces on communication lines is made a matter of simple arithmetic. The "K-m" Chart should prove of great value in all interference problems.—Editor.

Introduction

If in a grounded neutral power system one phase conductor becomes short-circuited to ground, a circuit will be established through the neutral and the earth, and a sudden shifting of currents will follow, changing the initial approximately balanced condition to a large unbalanced one which will persist until the fault is cleared. At the time of such abnormal conditions in a power circuit, a heavy electromagnetic induction is often introduced in a neighboring electric communication circuit. The disturbance attenuates to a steady state after a short period of transients. The magnitude of the inductive effect depends mainly upon the magnitude of the short-circuit current, and the relative position of the disturbing and disturbed lines, while the inductive effect due to transients follows the nature of the transient state of the current in the power line.

The theoretical computation of the voltage induced in an aerial line by a current flowing in a neighboring circuit consisting of another aerial line and the earth, involves many factors not readily determined. We often encounter the case, however, where the computation of the voltages induced in an aerial communication line by neighboring power currents is needed. It is therefore of value to simplify the calculation as much as possible by any means available, and by such assumptions and approximations as are permissible in practice.

Computation of the Induced Electromotive Force

In Fig. 1, let A_1 A_2 A_{20} A_{10} be the disturbing circuit consisting of the overhead conductor A_1 A_2, with the earth A_{20} A_{10} as a return circuit; and let a_1 a_2 a_{20} a_{10} be the disturbed circuit. One terminal a_2 is connected directly to the earth at a_{20}, while the other terminal a_1 is connected to the earth at a_{10} through a static voltmeter. The indication of voltmeter V will then be the vector sum of (a) the induced electromotive force in the aerial portion $a_1\ a_2$, and (b) the potential difference between a_{10} and a_{20}.

The induced electromotive force in the overhead conductor $a_1\ a_2$ depends upon the relative location of the two circuits, and the potential difference between a_{10} and a_{20} depends upon the distribution of the earth return currents and the positions of a_{10} and a_{20} with respect to A_{10} and A_{20}. Thus we may, for the computation of induced voltage V, consider the induced electromotive force in $a_1\ a_2$ separate from the potential difference between a_{10} and a_{20}.

The formula for the induced electromotive force in $a_1\ a_2$ may be written by making the following assumptions (see Fig. 2):

(a) That the electromagnetic effect at any point above the earth's surface, due to the current in a disturbing circuit, is equivalent to the combined effect of the current in that circuit and its image which is referred to the equivalent earth plane at the depth of D.

(b) That disturbing and disturbed lines are straight and parallel to the earth plane.

(c) That the charging current in the disturbing circuit is neglected.

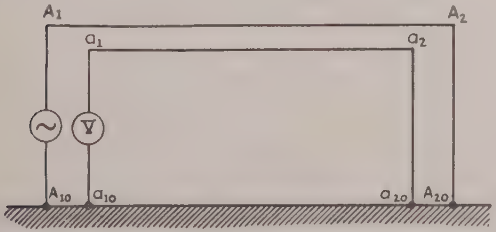


Fig. 1. Elementary Diagram of an Exposure Which Will Result in Inductive Interference

Case I: Let the disturbed and disturbing lines be parallel as shown in cross-section in Fig. 2. Then the induced electromotive force is given by

$$V = 2\pi f \times 2I \times l \times \log_\epsilon \frac{A'a}{Aa} \qquad (1)$$

where I is the current in the disturbing line and l the length of the exposure between the two lines. In Fig. 2, A and a are the disturbing and disturbed lines respectively, and A' is the image of A with respect to the equivalent earth plane $E_0\ E_0$. And if we let

H_1 = Height of disturbing line above the equivalent earth plane,

H_2 = Height of disturbed line above the equivalent earth plane, and

Y = Horizontal separation between the two lines, then

$$V = 2\pi f \times 2I \times l \times \log_\epsilon \sqrt{\frac{(H_1+H_2)^2+Y^2}{(H_1-H_2)^2+Y^2}} \qquad (2)$$

Putting

$$\left.\begin{aligned} H &= H_1+H_2 \\ h &= H_1-H_2 \\ m^2_0 &= \frac{h^2+Y^2}{H^2-h^2} \end{aligned}\right\} \qquad (3)$$

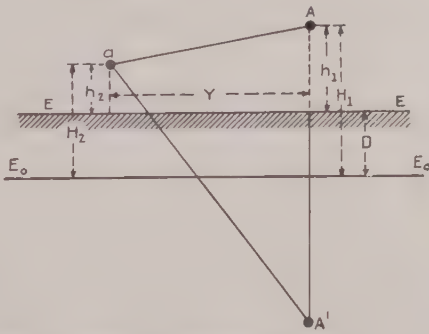


Fig. 2. Method of Establishing Power-line Image and Equivalent Earth Plane

We have from equations (2) and (3):

$$V = 2\pi f \times I \times l \times \log_\epsilon\left(1+\frac{1.}{m^2_0}\right) \qquad (4)$$

or

$$\frac{V}{l \times I} = 2\pi f \times \log_\epsilon\left(1+\frac{1}{m^2_0}\right) \qquad (5)$$

If $H_1 = H_2$, then $h = 0$. Putting $m_1 = \frac{Y}{H}$ equation (5) becomes

$$V = 2\pi f \times I \times l = \log_\epsilon\left(1+\frac{1}{m^2_1}\right) \qquad (6)$$

Now in Fig. 3 it is evident from the principle of super-position that the induced electromotive force in a disturbed conductor a, due to current $+I$ in A and $-I$ in A', is equal to the induced electromotive force due to a current $+I$ and $-I$ in A and A'' respectively, plus the induced electromotive force due to currents $-I$ and $+I$ in A'' and A' respectively. Thus if we let

$$\left.\begin{aligned} m_1 &= \frac{Y}{H} \\ \text{and} \\ m_2 &= \frac{Y}{h} \end{aligned}\right\} \qquad (7)$$

the induced electromotive force in a disturbed conductor due to $+I$ in A and $-I$ in A' will be given by

$$V=2\pi f\times I\times l\times\log_\epsilon\left(1+\frac{1}{m^2{}_2}\right)\qquad(8)$$

From equations (3), (6) and (8), we have

$$V=2\pi f\times I\times l\times\log_\epsilon\left(1+\frac{1}{m^2{}_0}\right)$$

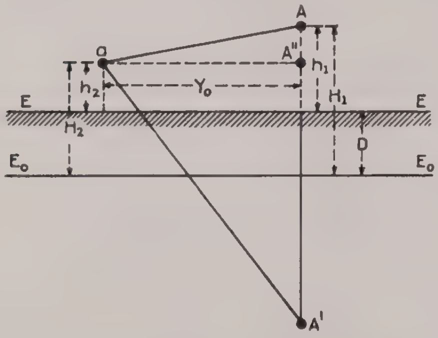


Fig. 3. Cross-sectional Diagram for the Case Where Disturbing and Disturbed Lines are Parallel

This equation is the same as equation (4), obtained previously.

Case II: Let the disturbing line and the disturbed line be not parallel, as in Fig. 4. Then the induced electromotive force is given by

$$V=2\pi f\times I\int_{-\frac{l}{2}}^{\frac{l}{2}}\log_\epsilon\frac{H^2+Y^2}{h^2+Y^2}\,dx\qquad(9)$$

Now if both lines are of the same height,

$$H_1=H_2\text{ and }h=0$$

Then

$$V=2\pi f\times I\int_{-\frac{l}{2}}^{\frac{l}{2}}\log_\epsilon\left(1+\frac{H^2}{Y^2}\right)dx\qquad(10)$$

Let θ=angle between the disturbing and disturbed lines; and let $\tan\theta=\alpha$.

$$Y_0=\frac{Y_1+Y_2}{2}$$

Then

$$\left.\begin{aligned}Y&=Y_0+\alpha x\\Y_1&=Y_0-\frac{\alpha l}{2}\\Y_2&=Y_0+\frac{\alpha l}{2}\end{aligned}\right\}\qquad(11)$$

From equations (10) and (11), we have

$$V=2\pi f\times I\times\frac{1}{\alpha}\int_{Y_0-\frac{\alpha l}{2}}^{Y_0+\frac{\alpha l}{2}}\log_\epsilon\left(1+\frac{H^2}{Y^2}\right)dY\qquad(12)$$

Integrating equation (12), we get

$$\begin{aligned}V&=2\pi f\,\frac{I}{\alpha}\left[Y\log_\epsilon\left(1+\frac{H^2}{Y^2}\right)+2H\tan^{-1}\frac{Y}{H}\right]_{Y_0-\frac{\alpha l}{2}}^{Y_0+\frac{\alpha l}{2}}\\&=2\pi f\,\frac{I}{\alpha}\Bigg[\left(Y_0+\frac{\alpha l}{2}\right)\log_\epsilon\left(1+\frac{H^2}{\left(Y_0+\frac{\alpha l}{2}\right)^2}\right)\\&\quad-\left(Y_0-\frac{\alpha l}{2}\right)\log_\epsilon\left(1+\frac{H^2}{\left(Y_0-\frac{\alpha l}{2}\right)^2}\right)\\&\quad+2H\left\{\tan^{-1}\frac{Y_0+\frac{\alpha l}{2}}{H}-\tan^{-1}\frac{Y_0-\frac{\alpha l}{2}}{H}\right\}\Bigg]\end{aligned}$$

Now let

$$\left.\begin{aligned}m_1&=\frac{Y_0}{H}\\p&=\frac{\alpha l}{2\,Y_0}\end{aligned}\right\}\qquad(13)$$

Then

$$\begin{aligned}V=2\pi f\times l\times I\times\frac{1}{2p}\Bigg[&(1+p)\log_\epsilon\left(1+\frac{1}{m_1{}^2(1+p)^2}\right)\\&-(1-p)\log_\epsilon\left(1+\frac{1}{m_1{}^2\,(1-p)^2}\right)\\&+\frac{2}{m_1}\left\{\tan^{-1}m_1\,(1+p)-\tan^{-1}m_1(1-p)\right\}\Bigg]\end{aligned}\qquad(14)$$

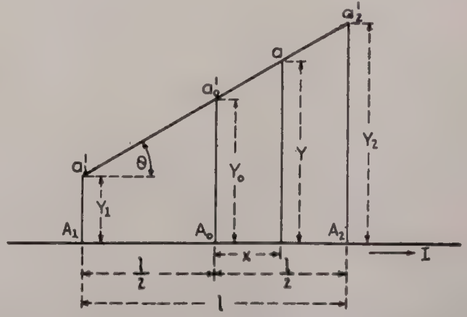


Fig. 4. Plan View of an Exposure Where Disturbing and Disturbed Lines Are Not Parallel

or

$$\begin{aligned}\frac{V}{I\times l}=2\pi f\,\frac{1}{2p}\Bigg[&(1+p)\log_\epsilon\left(1+\frac{1}{m_1{}^2\,(1+p)^2}\right)\\&-(1-p)\log_\epsilon\left(1+\frac{1}{m_1{}^2\,(1-p)^2}\right)\\&+\frac{2}{m_1}\left\{\tan^{-1}m_1(1+p)-\tan^{-1}m_1(1-p)\right\}\Bigg]\end{aligned}\qquad(15)$$

Equation (15) represents the induced electromotive force in the disturbed conductor, per unit of current in the disturbing circuit per unit length of the exposure.

If the heights of the two lines are not equal, the induced electromotive force is

$$V=\Big[(K)_{m1}-(K)_{m2}\Big]I\times l \qquad (16)$$

where

$$K=2\pi f\times\frac{1}{2p}\Bigg[(1+p)\log_e\left(1+\frac{1}{m^2(1+p)^2}\right)$$
$$-(1-p)\log_e\left(1+\frac{1}{m^2(1-p)^2}\right)$$
$$+\frac{2}{m}\{\tan^{-1}m\,(1+p)\pm\tan^{-1}m\,(1-p)\}\Bigg] \qquad (17)$$

and

$$m_2=\frac{Y}{h} \qquad (18)$$

If we take the case where a disturbing line $A_1\,A_2$ and a disturbed line $a_1\,a_2$ do not cross each other, $Y_0\neq 0$. Therefore the following conditions must always be satisfied,

$$m>0 \text{ and } 0<p<1$$

Evaluating equation (16) for the limiting value of $p=0$, we have

$$\lim_{p=0}V=2\pi f\times I\times l\Bigg[\log_e\left(1+\frac{1}{m_1^2}\right)$$
$$-\log_e\left(1+\frac{1}{m_2^2}\right)\Bigg] \qquad (19)$$

or

$$=2\pi f\times I\times l\times\log_e\left(1+\frac{1}{m_0^2}\right)$$

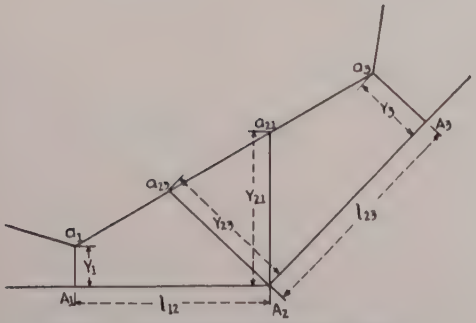


Fig. 5. Exposure with Bending Points in Both Lines

For $p=0$, the disturbing and disturbed lines are parallel; therefore equation (4) is a special case of equation (16). The limiting value of equation (16) for $p=1$, or for the case of Y_1 or Y_2 equal to zero, is given by $\lim_{p=1}V$, which is equal to

$$2\pi f\times I\Bigg[\Bigg[\log_e\left(1+\frac{1}{2m_1^2}\right)+\frac{1}{m_1}\tan^{-1}2m_1\Bigg]$$
$$-\Bigg[\log_e\left(1+\frac{1}{2m_2^2}\right)+\frac{1}{m_2}\tan^{-1}2m_2\Bigg]\Bigg]$$

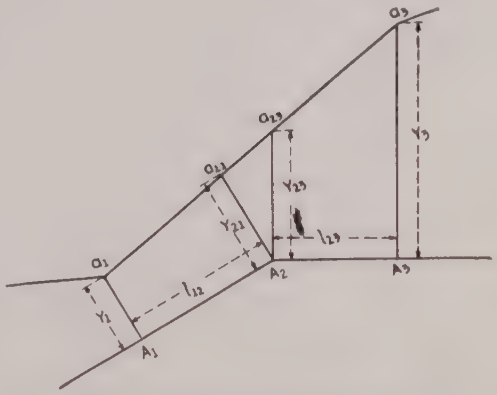


Fig. 6. Method of Sectionalizing an Exposure at Its Bending Points

If we measure V in volts, I in amperes, and l in km., then from equations (16), (17), (19), and (20), we have

$$\frac{V}{I\times l}=\Big[(K)_{m=m_1}-(K)_{m=m_2}\Big] \qquad (16a)$$

$$\left(\frac{V}{I\times l}\right)_{p=0}=\Big[(K)_{\substack{m=m_1\\p=0}}-(K)_{\substack{m=m_2\\p=0}}\Big] \qquad (19a)$$

$$\left(\frac{V}{I\times l}\right)_{p=1}=\Big[(K)_{\substack{m=m_1\\p=1}}-(K)_{\substack{m=m_2\\p=0}}\Big] \qquad (20a)$$

where K equals

$$2\pi f\times 10^{-4}\frac{1}{2p}\Bigg[2.3\,(1+p)\log_{10}\left(1+\frac{1}{m^2(1+p)^2}\right)$$
$$-2.3\,(1-p)\log_{10}\left(1+\frac{1}{m^2(1-p)^2}\right)$$
$$+\frac{2}{m}\{\tan^{-1}m\,(1+p)-\tan^{-1}m\,(1-p)\}\frac{\pi}{180}\Bigg] \qquad (17a)$$

Then we obtain from equation (17a) a series of curves (as shown in Fig. 7 for $f=50\sim$) for certain values of f representing the relations between K and m taking p as the parameter. Using this *K-m* relation, or K-m chart, Fig. 7, we can easily compute the induced electromotive force in a disturbed line when m and p are given. As Fig. 7 shows, the

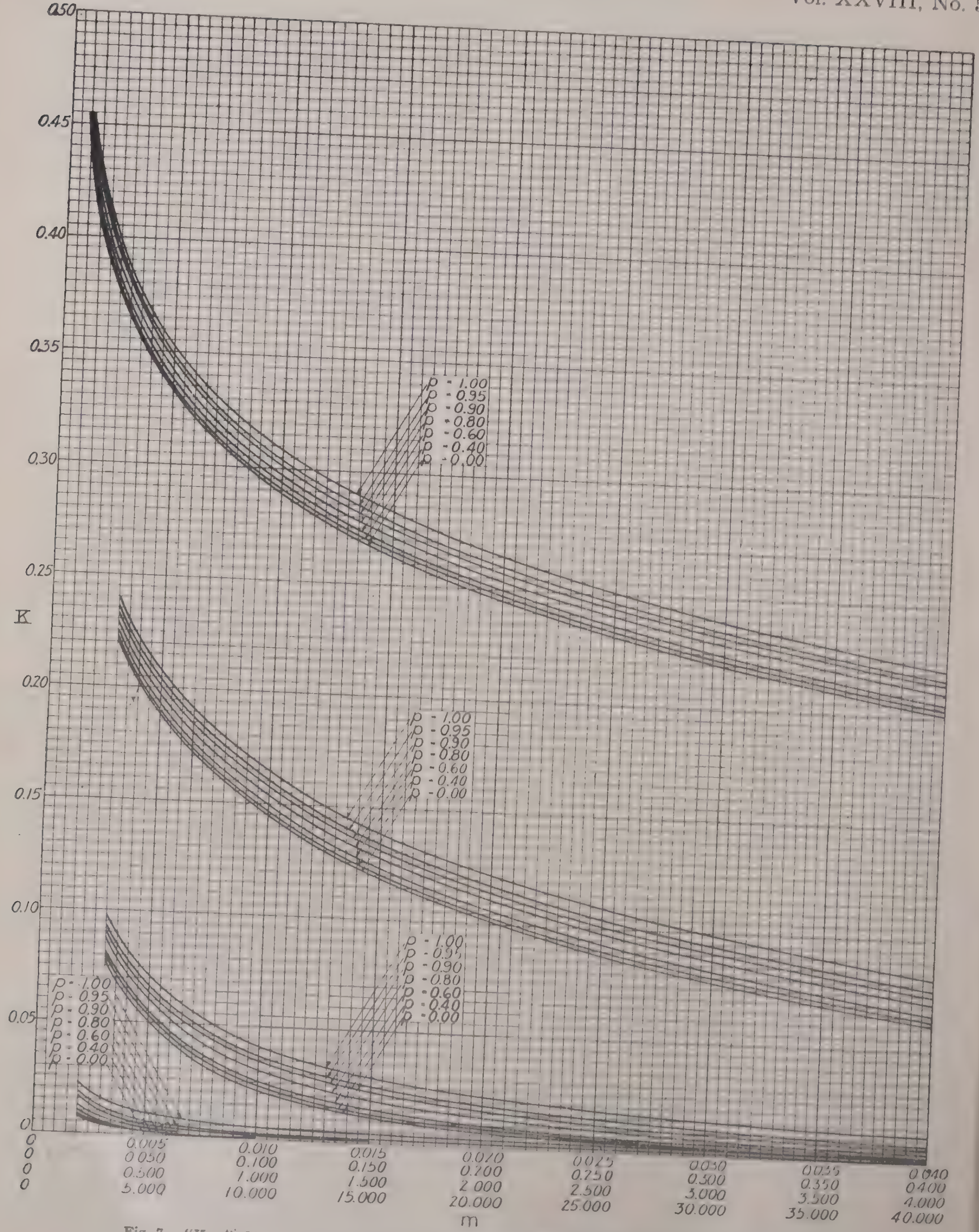


Fig. 7. "K-m" Chart, by Means of Which the Induced Electromotive Force in Each Section of an Exposure May be Readily Computed

value of K is very small for larger values of m. If Y_0 is very large compared with h or H_1-H_2, we may put

$$\frac{V}{I\times l}=(K)_{m=m_1}$$

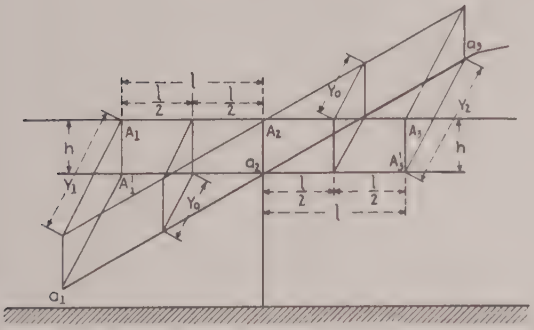


Fig. 8. Diagram of Exposure Where Disturbed Line is Not Horizontal

When both lines have many angles and crossing points, we must compute $\frac{V}{I\times l}$ for each exposure, which is sectionalized by two adjacent parallel planes perpendicular to the disturbing line passing through every bending point in both lines and through every crossing point. For example, consider the cases of relative location of the two lines as shown in Figs. 5, 6 and 8. Let $A_1\ A_2\ A_3$ and $a_1\ a_2\ a_3$ be the disturbing and disturbed lines respectively. In Figs. 5 and 6, let $A_1\ a_1$ and $A_2\ a_{21}$ represent two adjacent parallel planes perpendicular to $A_1\ A_2$ which pass through bending points A_2 and a_1, and let $A_2\ a_{23}$ and $A_3\ a_3$ be those perpendicular to $A_2\ A_3$. Then the relative location of the two lines may be considered as shown in Fig. 9 and Fig. 10.

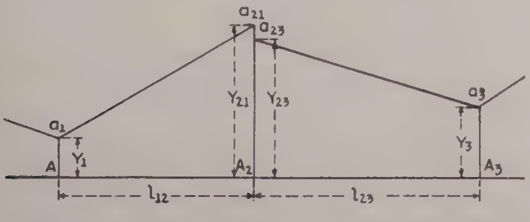


Fig. 9. Method of Unfolding the Exposure so That the Power Circuit Becomes a Single Straight Line

In the case shown in Fig. 8, consider the induction for each exposure sectionalized at the crossing point. As the value of p always satisfies the condition of $m>0$ and $0<p<1$, we can compute the induction by using the K-m chart.

Numerical Example No. 1

The relative locations of disturbing line and disturbed line are shown in Fig. 11.

The height of the disturbing line above the earth's surface is

$$h_1=12 \text{ meters.}$$

The height of the disturbed line is

$$h_2=6\ m.$$

Assume the depth of the equivalent earth plane as

$$D=400\ m.$$

Then

$$H_1=h_1+D=412\ m.$$
$$H_2=h_2+D=406\ m.$$
$$H\ =H_1+H_2=818\ m.$$
$$h\ =H_1-H_2=6\ m.$$

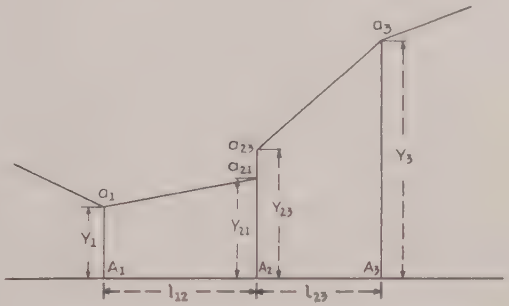


Fig. 10. An Exposure Sectionalized and Ready for Computation

For the nth section,

$$Y=\frac{Y_r+Y_{r_1}}{2}$$

$$p_r=\frac{a_r\,l_r}{2\,Y_{0r}}=\frac{Y_r-Y_{r_1}}{Y_r+Y_{r_1}}$$

$$m_{1r}=\frac{Y_{0r}}{H}$$

and $$m_{2r}=\frac{Y_{0r}}{h}$$

We can obtain the values of $(K)_{m=m_{1r}}$ and $(K)_{m=m_{2r}}$.

Then $$\left(\frac{V}{I\times l}\right)_r=(K)_{m=m_{1r}}-(K)_{m=m_{2r}}$$

or $$\left(\frac{V}{I}\right)_r=l_r\left[(K)_{m=m_{1r}}-(K)_{m=m_{2r}}\right]$$

Thus, for the whole length of the exposure, we obtain

$$\frac{V}{I}=\sum_1^n r\,l_r\left[(K)_{m=m_{1r}}-(K)_{m=m_{2r}}\right]$$

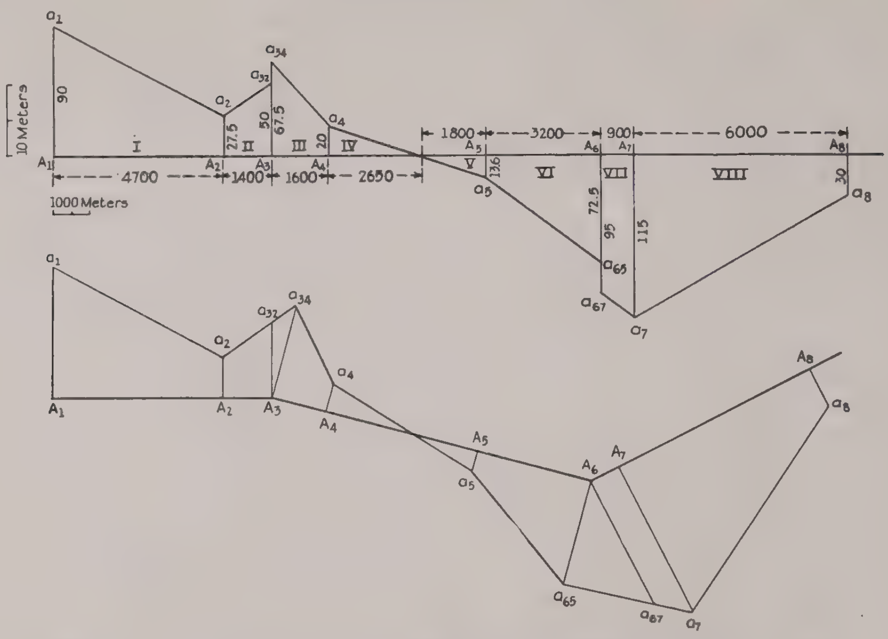


Fig. 11. An Actual Exposure with its Rearrangement for Solution by the "K-m" Chart. The lower drawing gives the original geographic shape of the exposure, which is resolved into the sectionalized diagram above

TABLE I

CALCULATING TABLE

$h_1 = 12$ m.
$h_2 = 6$ m.

$D = 400$ m.

$H = 2\ (h_1 + D) = 818$ m.
$h = 2\ h_1 - h_2 = 6$ m.

Section No.	Y	l	Y_{0r} $\left(= \frac{Y_1+Y_2}{2}\right)$	P_r $\left(= \frac{Y_1-Y_2}{Y_1+Y_2}\right)$	m_{1r} $\left(= \frac{Y_{0r}}{H}\right)$	m_{2r} $\left(= \frac{Y_{0r}}{h}\right)$	$(K)m = m_{1r}$	$(K)m = m_{2r}$	$\left(\frac{V}{I}\right)_r$ $(= l_r[(K)_{m_{1r}} - (K)_{m_{2r}}])$
I	90 27.5	4.70	58.8	0.53	0.072	9.8	0.168	0.0015	0.78
II	27.5 50	1.40	38.7	0.29	0.0477	6.45	0.192	0.0015	0.267
III	67.5 20	1.60	43.7	0.54	0.0532	7.29	0.185	0.0020	0.293
IV	20 0	2.65	10.0	1.0	0.0122	1.67	0.245	0.027	0.58
V	0 13.6	1.80	6.8	1.0	0.0083	1.13	0.319	0.038	0.506
VI	13.6 72.5	3.20	43.1	0.68	0.0525	7.2	0.1915	0.002	0.612
VII	95 115	9.00	105	0.095	0.128	17.5	0.144	0.0005	1.30
VIII	115 30	6.00	42.5	0.59	0.052	7.07	0.190	0.0002	1.127

$$\sum \frac{V}{I} = 5.465$$

For simplicity in arranging the computations, and to assist in the use of the K-m Chart, the calculating sheet shown in Table I may be used.

TABLE II

EXPOSURE DATA, KOMABASHI-WASEDA LINE

Depth of Equivalent Earth Plane in Meters	INDUCED VOLTAGE PER AMPERE OF INDUCING LINE	
	I Telephone Line (Tokyo-Osaka No. 9)	II Telegraph Line (Tokyo-Kyoto No. 2)
100	1.03	1.58
200	1.80	2.69
300	2.45	3.57
400	3.02	4.33
500	3.52	5.03
600	3.94	5.62
700	4.32	6.14
800	4.67	6.62
900	4.97	7.06
1000	5.25	7.47

Numerical Example No. 2

Communication lines under Government control are more or less parallel to the Komabashi-Waseda 55,000-volt transmission line of the Tokyo Electric Light Co., and present over 100 sections of varying separation and angularity of exposure. The induced electromotive forces to be expected in the communication circuits were computed with the aid of the K-m Chart and the type of calculating sheet shown in Table I. The computations were repeated for various values of D, ranging from $D=100$ m. to $D=1000$ m.

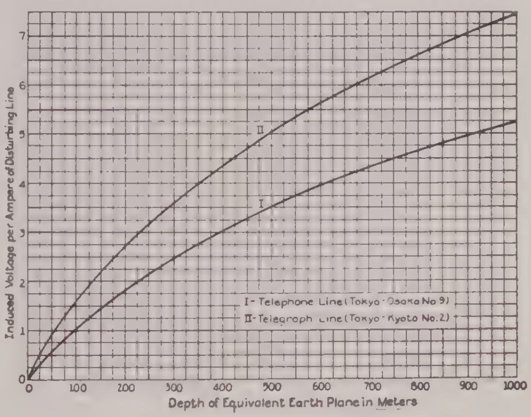


Fig. 12. Curves Showing the Relation of Induced Electromotive Force to the Depth of Equivalent Earth Plane for the Exposures Given in Table II

The results, expressed in volts per ampere induction for the whole exposure, are contained in Table II, and in graphic form in the plots of Fig. 13.

The analysis of this interference problem is especially valuable as a demonstration of the applicability of the K-m Chart.

A Transmission Line in Japan

Interest Charges During Construction

By W. H. Blood, Jr.
Stone & Webster, Incorporated

When the construction of a new power plant is under consideration there are a host of factors to be determined. We electrical engineers naturally give attention to the amount of possible load development and to the electrical dimensions of the plant in terms of kilovolt-ampere capacity, kilowatt-hour output per pound of coal burned, the operating power-factor, load-factor, etc. One of the other factors is that of finance and upon it rests the likelihood of the plant being built. Though we engineers are not burdened with the raising of the money, the bearing which this vital matter has upon our profession leads us to reprint from the January, 1925, issue of the *Stone & Webster Journal* the following article which analyzes one phase of the subject that is none too well understood.—Editor.

Practically all courts and commissions recognize the propriety of including interest during construction as an element of cost when determining the value of a public utility property. Money must be compensated for the service which it renders for exactly the same reason that labor has to be paid for its services. If the laborer does not get his pay envelope on Saturday night, he quits the job. If capital does not receive a satisfactory wage for the time it is at work, it looks for other fields. It would be absurd to expect a laborer to work without wages during the construction of a plant with the incentive that later on he might get a steady job with regular wages when the plant was put into operation. It is just as foolish to expect capital to work for nothing during the construction period with the promise of regular dividends when earnings from the completed plant come in. Capital demands and is entitled to its wages for all the time that it is employed, regardless of whether the plant for which the capital is expended is under construction or is a completed and operating whole.

When estimating the reproduction cost of a physical property we assume a definite number of man-hours to do a certain job and we figure the cost per hour based upon the going wages in the specific trades employed. We base our estimated costs on experience and the more experience we have had and the larger the number of construction jobs we have performed the more accurate is our estimate.

By a similar method interest during construction is a determination, based upon experience, of what it actually costs to use the money during the construction period. It is not theoretical; it is not hypothetical; it is just as susceptible of accurate ascertainment as is finding the cost of setting a boiler or of building a pole line. Unfortunately, some commissions and some engineers have not applied to this factor the same care in determination as they have to other items in appraisals, and as a result we find many valuations where arbitrary amounts are used which in turn form precedents for other similar proceedings. The purpose of this article is to point out the limits of the variables and also to show the effect upon the final results which are obtained by adopting various programs of procedure.

In ascertaining interest during construction there are three variables which must be considered—the rate of interest, the construction period, and when the money is raised. The rate of interest is fairly easy to fix at any given time. We must have in mind that we are determining the cost to reproduce the property, new, and it therefore follows that the present financial condition of the utility as a going entity does not concern us. We are forced to assume a new project without an established credit, consequently we must consider the risks involved in the business and we must recognize local or territorial conditions. In other words, we must determine an interest rate which is sufficient to attract capital to this particular enterprise located as it is. We must also plan to raise the money so as to have available at all times ample funds to carry on the construction program unhampered and to pay for labor and material as the demands are made.

Laying out a construction program is an every day occurrence with large engineering and construction organizations and is simply a determination of the most economical method of procedure in the construction of a given plant. Forced construction entails high costs, yet the shorter the period the smaller the interest charge; and, conversely, the longer the construction period, the larger the total amount of interest. Knowledge of business conditions and particularly exact information as to deliveries of material and apparatus are essential in laying out a construction program. Having determined the dates upon which the construction material will be available, one who has had experience can determine the number of men necessary for each particular undertaking. It is obviously uneconomical to have a gang of men waiting around for material to arrive. Likewise, material coming in ahead of time or off schedule is apt to entail additional costs for rehandling, storing, and the like.

The periods at which the money is raised are of prime importance. Unfortunately, this consideration is often ignored and it has become almost a habit with engineers and some commissions arbitrarily to allow six per cent (sometimes more, but frequently less) on the total cost for one-half the full time of construction. For the purpose of comparison as to the cost of interest during construction, let us admit for simplicity that the rate of expenditure is constant throughout the period. As a matter of fact, this substantially coincides with experience, although frequently the rates of expenditure at the start and at the end of a job are not as rapid as during the intermediate period.

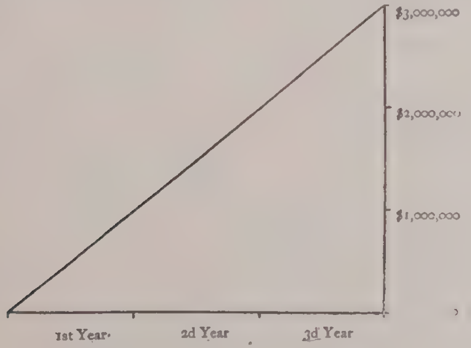


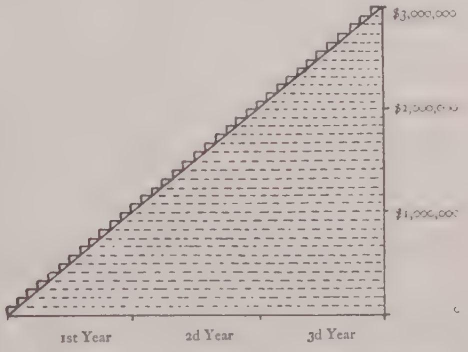
Fig. 1. Money Borrowed as Expended

Rate of interest paid	5%	6%	7%	8%
Interest at above rate on $3,000,000 for an average time equal to one-half the construction period, or 1½ years	$225,000	$270,000	$315,000	$360,000

Let us first assume that an arrangement has been made for the company to get the money day by day just as it is needed, that it has no idle cash and that all requirements are taken care of. There consequently would be no balances in the bank on which to draw interest. Such an arrangement does not exist in practice but it would be ideal, and if it could be made it would show the lowest cost of interest during construction. It would be equivalent to figuring interest at the going rate on the total cost for one-half the total time which, as stated previously, is not an uncommon assumption. This is shown graphically in Fig. 1.

Such an ideal condition as is suggested in Fig. 1 is hard for an experienced man to visualize, for it is not met in practice. It is purely theoretical but it is presented for the purpose of showing the minimum amount of interest during construction that would be possible.

In Fig. 2 the assumption is made that at the beginning of each month sufficient money is borrowed to pay for the work to be completed during the month, or, in other words, that 36 equal installments are made to keep pace with uniform monthly requirements.



g. 2. Money Borrowed in 36 Equal Installments

Rate of interest paid	5%	6%	7%	8%
Interest at above rate on 36 installments of $83,333 each for 36 periods of one month to 36 months respectively, (which is equivalent to $83,333 at above rate for 666 months, total)	$231,000	$278,000	$324,000	$370,000
Interest received on unexpended balances, negligible				
Net interest chargeable to construction	$231,000	$278,000	$324,000	$370,000

This method of raising money is also impracticable and is indicated simply to show that it costs a little more than the method suggested in Fig. 1.

On the assumption that a banker could be found who would advance money as needed at six months' intervals for the three-year construction period, we would be able to produce the chart shown in Fig. 3. Unless we assume extremely high rates of interest we are still dealing with theoretical methods of raising money, for in practice on an untried enterprise it would be difficult to find anyone who, at regular intervals, six months apart, would be willing to advance half a million dollars on request.

For the purpose of illustration we are carrying the plan of raising money one step further, which is that of raising the money by three borrowings, one year apart. This is shown in Fig. 4. We are now beginning to get into the realm of possibility, though if financing were done in this manner the banker would have to be amply paid for this accommodation.

When starting a new enterprise the general practice is to arrange for completely financing the proposition before the construction work actually begins, otherwise the promoter is liable to be caught in the lurch. Market conditions change from day to day, and while a banker might be willing to buy $3,000,000 bonds today at the agreed price he would expect to sell them within a reasonable time and would consider it too great a risk to agree to take three $1,000,000 lots at three intervals twelve months apart.

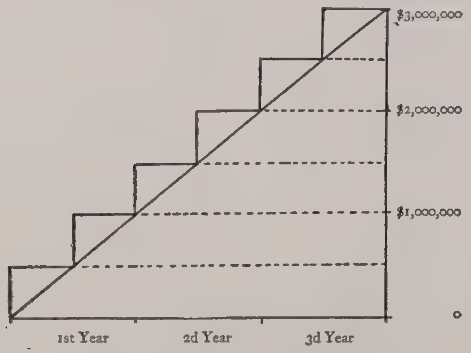


Fig. 3. Money Borrowed in 6 Equal Installments

Rate of interest paid	5%	6%	7%	8%
Interest at above rate on				
$500,000 for 3 years	$ 75,000	$ 90,000	$105,000	$120,000
500,000 " 2½ "	62,500	75,000	87,500	100,000
500,000 " 2 "	50,000	60,000	70,000	80,000
500,000 " 1½ "	37,500	45,000	52,500	60,000
500,000 " 1 "	25,000	30,000	35,000	40,000
500,000 " ½ "	12,500	15,000	17,500	20,000
Total	$262,500	$315,000	$367,500	$420,000
Interest received on unexpended balances assumed at 2%; six times $500,000 for an average time equal to one-half the period between installments, or ¼ year	15,000	15,000	15,000	15,000
Net interest chargeable to construction	$247,500	$300,000	$352,500	$405,000

There might be no bond market at the later dates, or the price he would be willing to make, due to changed financial conditions, might be such that the company could not afford to take it. The chart in Fig. 5 shows the way that money for such enterprises is actually provided and it will be noted that the real cost of interest during construction is materially more than that shown on the other charts, these other charts indicating theoretical methods of raising money. The entire amount of money is raised at one time through the sale of securities. This is placed on deposit with the bank and the bank knowing approximately when the money is to be withdrawn is willing to pay a high rate for its use.

A study of these charts shows that on the theory of interest on the full amount for one-half the time at the going rate of six per cent the total cost of interest during construction would be nine per cent or $270,000, while in actual practice raising money in the ordinary way the cost would be 12 per cent or $360,000.

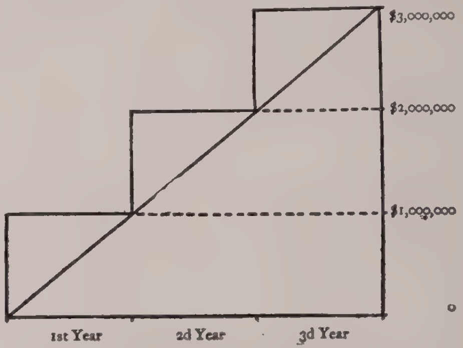


Fig. 4. Money Borrowed in 3 Equal Installments

Rate of interest paid	5%	6%	7%	8%
Interest at above rate on:				
$1,000,000 for 3 years	$150,000	$180,000	$210,000	$240,000
$1,000,000 " 2 "	100,000	120,000	140,000	160,000
$1,000,000 " 1 "	50,000	60,000	70,000	80,000
Total	$300,000	$360,000	$420,000	$480,000
Interest received on unexpended balances assumed at one-half the above rate paid; three times $1,000,000 for an average time equal to one-half the period between installments, or ½ year	38,000	45,000	53,000	60,000
Net interest chargeable to construction	$262,000	$315,000	$367,000	$420,000

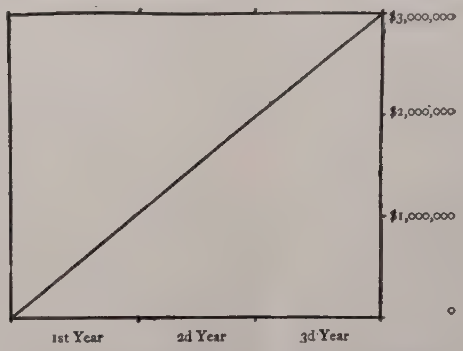


Fig. 5. Money Borrowed in One Sum at Beginning of Construction Period

Rate of interest paid	5%	6%	7%	8%
Interest at above rate on $3,000,000 for whole construction period or 3 years	$450,000	$540,000	$630,000	$720,000
Rate of interest received on unexpended balances assumed at	3½%	4%	4%	4%
Interest received at above rate on $3,000,000 for an average time equal to one-half the construction period, or 1½ years	158,000	180,000	180,000	180,000
Net interest chargeable to construction	$292,000	$360,000	$450,000	$540,000

There are minor adjustments which might properly be taken into account when figuring interest during construction. For example, it would be perfectly fair to assume that all the land had to be bought before construction work started, in which case interest during construction on the land would be figured on the full cost for the full time. It might likewise be assumed that rolling stock, for instance, on a railway property, would not be purchased until the construction work was practically completed and on this theory there would be little, if any, interest applicable to rolling stock. These are minor matters and do not affect the general principle that has been outlined.

Interest during construction is generally figured up to the time the plant goes into operation. It is well known, however, that few plants begin to earn a full return from the time they start. There is always a period while they are securing their customers, getting the plant operating efficiently, etc., when the return on the investment falls below the rate the utility is entitled to earn. This is generally recognized as part of the development cost. It is practically a continuation of interest during construction. It is an amount which should be taken into account when fixing the value of a public utility, but practice draws a sharp line between interest during construction and interest during development. The curves and data presented herewith have to do only with interest during construction.

The New Weymouth Generating Station Recently Built by Stone & Webster, Inc., for the Edison Electric Illuminating Company of Boston

A Simple Method of Calculating Magnetic Conditions in Electrical Machinery

By C. Macmillan

Induction Motor Engineering Department, General Electric Company

There is no problem in electrical engineering which has proved more stubborn, in the hands of theorists and practical men alike, than the determination of the fundamental law of ferro-magnetism. Almost without exception, the greatest scientific minds have attempted to formulate expressions which would fully cover all of the conditions met in practice, but none of them have attained more than partial success. The literature is therefore filled with empirical formulas, each of which is meant to cover only a certain range of the magnetic phenomena. Mr. Macmillan here proposes a new empirical law which combines the virtues of many previous laws, with a special adaptability to the type of magnetic problems met in the design of induction motors. —Editor.

The magnetic properties of iron may be numbered among the important assets of an industrial civilization. By a fortunate coincidence, the same metal which had already given its name to the Iron Age was found to possess those properties which made possible the advent of the Electrical Age.

In view of their practical importance, it is not strange that magnetic phenomena should enlist the continued interest of physicists and engineers. This interest is maintained and heightened by the elusive nature of the subject. Despite the patient efforts of the ablest investigators, the basic law of strongly magnetic materials remains a mystery. It is no idle curiosity which persists in attempts to solve the mystery, for iron in spite of its very valuable magnetic characteristics has one or two unfortunate failings. These constitute a permanent tax upon our utilization of power. The practical utility of magnetism in iron depends upon the intensity and the rapidity of reversal which can be secured, and unfortunately each of these requirements involves the continuous dissipation of power.

One principal object of the designer of electrical machinery is to reduce these losses to the greatest possible extent. In this direction his efforts are greatly hampered by the lack of any known laws which might serve to explain rationally the facts upon which the losses in question depend.

To Dr. C. P. Steinmetz electrical engineers of today owe the empirical law which bears his name, the Law of Hysteresis. It may be difficult to realize with what gratitude their predecessors greeted its publication, as the first useful light to illumine a region of very black darkness. For the remaining losses involved in excitation, we have not even an empirical law of equal validity to guide us. Many have been proposed, but none has met with sufficient success to earn for it a place among the universally recognized resources of the designing engineer.

Some of these proposals reveal the fascination exercised upon their authors by another peculiar magnetic property of iron generally known as saturation. There are simple laws of elasticity, of conductivity, of electrostatic capacity, etc., which represent various physical characteristics of materials with remarkable accuracy within their respective ranges of application. Elastic materials bend and break, conductors burn out or melt, insulators break down. Sometimes it is the law which breaks down first, sometimes the material, but sooner or later, under increasing abuse, one or the other of them fails. Not so with magnetic material. It has never been magnetized to the point of destruction nor are there any immediate prospects of such a climax being reached. On the contrary the greater the efforts put forth, the safer, more stable and more reliable are both the material and the simple law appropriate to these special conditions. Of the law we simply say: $B-H=$ a constant, of the material we say with impunity that it cannot be injured.

As a result of this special interest in the phenomena of saturation less attention has been paid to the practical need for laws which would accurately represent the conditions at moderate magnetic densities such as those most frequently employed in electrical machines.

In the electrical design of induction motors of outputs ranging from 10 h.p. to over 20,000 h.p., the writer has developed some equations of a novel type which have proved very serviceable in the analysis of magnetic characteristics. Hopkinson's treatment of the magnetic circuit as a group of simple reluctances in series provides a useful approximation to the facts of the case. With the aid of Carter's formulas for fringing, and other refinements which have been added from time to time, the designer is well equipped to deal with the majority of the problems encountered in standard practice. In some special problems, however, such as those encountered in the design of electric ship propulsion equipment, the need for some supplementary methods arises. After much experimenting with such empirical formulas as those due to Kennelly, Deri and others, the equations referred to were devised and adopted. Subsequent experience indicates that they are capable of furnishing a clearer insight into the behavior of iron, steel and magnetic alloys under a variety of conditions of operation than any others at present available. Although devised to deal with special problems, it is believed that these equations will be found valuable in regular designing practice, in the analysis of test results, and for other purposes.

The most general basic equation may be written in the form

$$B-H=c\log\left(+\sqrt{\left(\frac{H}{H_c}\pm 1\right)^2}\right)+b \qquad (1)$$

Until recently the writer was unacquainted with very similar equations published by M. Deri many years ago, having the logarithmic form and with coefficients corresponding to b and c in (1). He has been familiar with the customary method of plotting $B-H$ graphs upon semi-log paper, as suggested by Dr. C. P. Steinmetz, Mr. J. D. Ball, and others. Such graphs illustrate the deviation which may be expected from equations of the logarithmic type with coefficients in the form of factors. Attention should be specially directed to the additive term H_c. The special practical and theoretical significance of this modification will be illustrated in later paragraphs. Here, however, it may be noted that the term $+\sqrt{\left(\frac{H}{H_c}\pm 1\right)^2}$ permits the equation to retain its basic form while representing, with suitable values of b and c, first, the three ascending ranges of the magnetizing curve, second, the six ranges which constitute the hysteresis loop, third, these nine ranges in materials varying from permalloy to Honda Cobalt magnet steels.

The magnetic diversity of these materials is roughly indicated by the ratio of their maximum hysteresis loop widths at corresponding maximum densities, which is of the order of 1500/1.

The writer also discovered with some surprise that complete induction motors could be treated as if they were simple samples of magnetic material with air gap reluctances in series. Consequently, if a properly estimated deduction is made for the amperes required by the air gap, the net amperes obtained from a test excitation curve may be used to plot against terminal volts, on semi-log paper in the form of a line which is nearly straight. For many purposes it is unnecessary to correct this curve for the small values of H_c appropriate to good qualities of steel punchings. For checking test results, eliminating unreliable test readings, verifying air gap estimates, noting saturation effects, interpolating and extrapolating this derived curve will be found to possess many advantages in the range of higher magnetic densities. For lower densities, $H-H_c$, or the corresponding values of magnetizing current I_m-I_{mc} should be used instead of H or I_m.

Similar methods applied to the test results obtained from turbine generators illustrating a wide range of design yield equally satisfactory graphs on semi-log section paper. These generators may be taken as representative of electromagnetic conditions as remote as possible from those first encountered in induction motors. It follows that phenomena recognized as common to these extreme cases probably occur in a large variety of intermediate cases.

The comparison of such derived curves obtained from test results, with calculated results based on the Hopkinson summation in the usual way, will provide for suitable modifications of the equation coefficients necessitated by the complex magnetic circuits of complete machines.

Sufficient data have not yet been accumulated to warrant assigning definite numerical values to these coefficients for general use. Most designers will prefer to adopt constants in agreement with the materials, standard data and factors of safety to which they are accustomed. Having adopted suitable constants checked by experience, they will find that no charts are required for calculation of magnetization, since the basic law is that of the slide rule.

As an illustration of the logarithmic plotting of test results the excitation curves of three commercial induction motors are given in Figs. 1, 2 and 3.

These were 6-pole motors using the same punchings with different lengths of core. They were wound for 2200 v. and rated 100, 150, and 200 h.p. respectively. The magnetic material was silicon steel. The shop

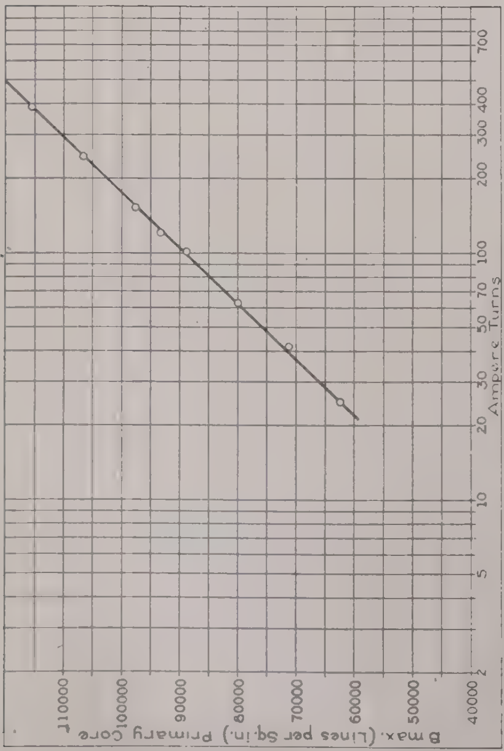


Fig. 1. 100-h.p. Motor, Silicon Steel

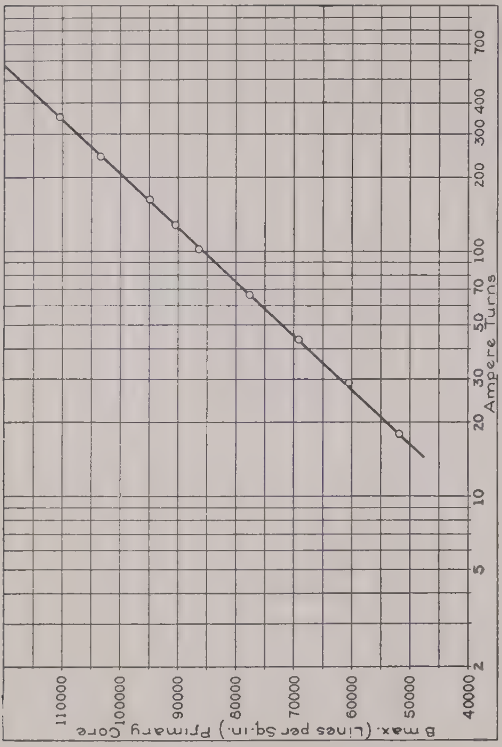


Fig. 2. 150-h.p. Motor, Silicon Steel

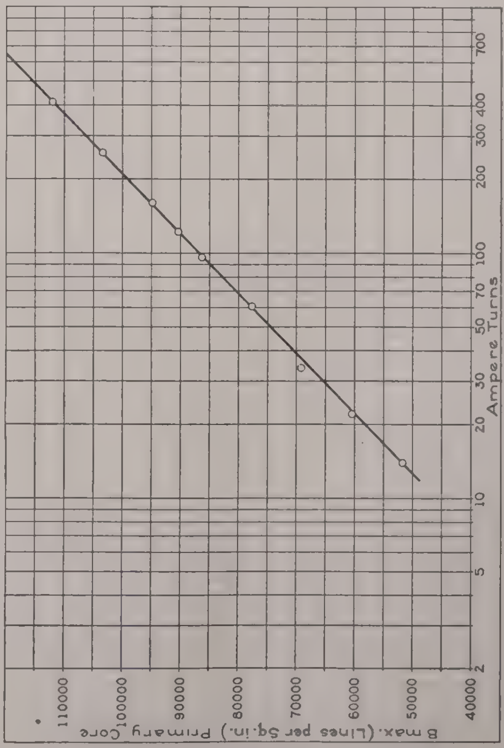


Fig. 3. 200-h. p. Motor, Silicon Steel

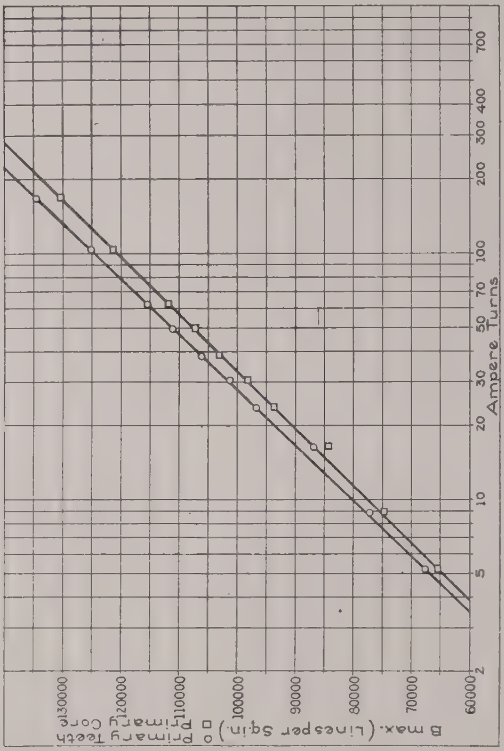


Fig. 4. 600-h.p. Motor, Standard Steel

Net Iron Magnetization Curves of Standard Induction Motors measurements of air gap gave, respectively, 4, 5 and 5 mils less than the designed value. It was therefore assumed that the true magnetic gap was in accordance with the design, since shop measurements are usually small by about the amount indicated.

Since no reliable laboratory data for the particular steel used was available, a value of 1.4 amp.-turns per in. was assumed for H_c. The total equivalent magnetic length of iron was estimated at 14.25 in. so that $H_c \times l$ was estimated at 20 amp.-turns.

From the test values were computed volts per phase, current, primary leakage reactance, and values of e, the volts per phase corresponding to net air gap flux, and from the corresponding total amp.-turns per pole a deduction proportional to e was made to allow for estimated air gap reluctance. A further deduction of 20 amp.-turns gave a net value representing the variable portion of total amp.-turns required for the iron magnetic circuit, represented by a.-t_{Fe}. In order to obtain a more direct comparison, values of B_{PC}, the maximum densities in lines per sq. in. for the yokes, were tabulated. They are proportional to volts per phase, for each motor, but for the same terminal voltage are not the same in all three motors. When the maximum magnetic densities in the various parts of the magnetic circuit of a motor are approximately equal and the leakage factor is small, either core density or tooth density may be used as a basis for plotting, with satisfactory results. When the densities differ considerably or when the leakage factor is high, the matter is not so simple. The best results may be obtained by selecting probable coefficients for the material employed and calculating the expected values of total amp.-turns required from the equation given. From a few values, a graph may be drawn of the expected magnetization. A second graph of test amp.-turns against calculated values will then show clearly any deviation from expected results.

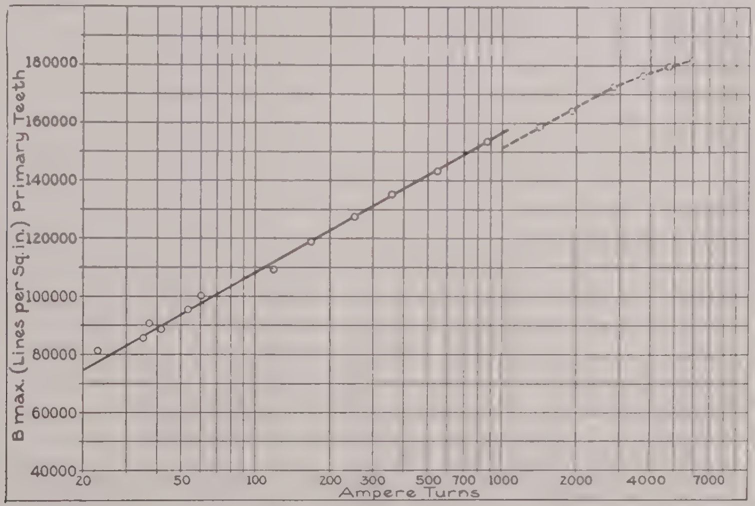


Fig. 5. Net Iron Magnetization Curves of 150-h.p. Motor with Standard Core Iron

A few graphs for other motors have been added. Fig. 4 refers to a 4-pole motor of 600 h.p. using standard steel. The densities were slightly higher. The effect of friction on the two lowest points was calculated and amounted to less than 5 per cent in current.

The points as plotted represent the corrected values, and fall in line with those at higher densities which are unaffected by friction. Fig. 5 refers to a 16-pole motor rated at 150 h.p. which was tested to much higher densities and for which a curve of reactance at high current densities was also available showing reduction to 2/3 of the maximum value at the highest densities used. This reactance curve was used in estimating the primary reactance drop, and its effect on air gap density. The graph indicates that there was probably a still greater reduction of reactance by saturation on account of the fact that portions of the magnetic circuit were carrying useful flux and leakage flux simultaneously. The graph is plotted against primary tooth density as a convenient base, but this is not strictly justifiable since the total amp.-turns depend also on other parts of the magnetic circuit at other densities. The discontinuity at $B=155{,}000$ was not noticed while the motor was in test. It corresponds with a change of ammeter transformers and probably also to some mistake in test procedure. It has been included partly to indicate how clearly discrepancies may be recognized which are easily overlooked when test results are checked by the usual methods.

Fig. 6 shows that equally high apparent maximum densities may be reached without departure from the rectilinear graph. This 4-pole 20-h.p. motor was designed for approximately uniform magnetic densities throughout, in marked contrast to the previous example, in which the yoke densities were abnormally low relative to the corresponding tooth densities.

Fig. 7 represents the data obtained on a multispeed motor wound for 8 and also for 24 poles. With the latter connection the yoke amp.-turns are negligible. With the former they constitute the major portion of the total magnetizing amp.-turns. In spite of this difference, the parallel graphs, as drawn, represent the data up to high apparent densities to a satisfactory degree of accuracy. The scattering of points in the lower ranges indicates less care in testing than is exhibited by the other graphs.

These curves are all based on commercial test data, and no particular steps were taken to secure the degree of accuracy which is desirable in tests specially intended for analysis by the methods indicated above. The coefficients required for the iron equation will vary not only with the quality of steel used, but also with many of the features of design, so that no standard values can be assigned. In Table I are given values for coefficients b and c (in terms of kilolines per sq. in. and amp.-turns per inch) which have been found appropriate in a number of cases.

TABLE I

	b	c	($B=30{,}000$ to $B=60{,}000$) a.-t$_{c}$.	($B=60{,}000$ to $B=120{,}000$) a.-t$_{c}$.
Standard sheet steel.......	50	50	1.0	1.4
	45	50		
Silicon steel..	50	45	1.0	1.4
	45	42		

When representing an a-c. magnetization curve, the general logarithmic equation may be written in somewhat simpler form, namely $B-3.2$ a.-t./in.$=c\log$ (a.-t./in.$-$a.-t$_{c}$.)$+b$, since a.-t$_{c}$. is always positive and less than a.-t./in. within the range required.

Several graphs illustrated show apparent maximum densities which do not represent actual magnetic conditions since they are above the saturation capacity of the materials used. In the case of the 20-h.p. motor the maximum apparent density in the teeth is 180,000 lines per sq. in., whereas the saturation value of the steel probably does not exceed 120,000. The actual magnetic distribution must differ greatly from the true sinusoidal form. It is therefore remarkable that these hypothetical densities furnish a suitable base upon which the logarithms of the amp.-turns show very approximate proportionality.

AN EMPIRICAL LAW OF FERROMAGNETISM

The foregoing paragraphs and Figs. 1 to 7 are based upon the tentative adoption of a simple hypothesis as to the intrinsic relation between H and I in ferromagnetic materials.

This hypothesis may be embodied in an equation of the form

$$I=c\log\left(+\sqrt{(H\pm H_c)^2+b_l}\right)$$

or

$$B-H=c\log\left(+\sqrt{(H\pm H_c)^2+b}\right) \qquad (2)$$

A more general differential form obtained by ignoring one constant is:

$$dH/d\,(B-H)=+\sqrt{\frac{(H\pm H_c)^2}{c}} \qquad (3)$$

The primary purpose of such empirical equations is to condense considerable masses of observed data into concise forms. The concentration of pertinent material greatly facilitates the formulation of a rational theory, and in the field of ferromagnetism an adequate theory is urgently required. Unfortunately none of the brilliant hypotheses based upon the electron theory have secured quantitative agreement between the theoretical results and the everyday experience of the electrical engineer. This is rather remarkable in view of the very satisfactory corroboration which some of these hypotheses have received in many fields of experimental physics.

The variable permeability of ferromagnetic materials introduces a factor into electrical engineering calculations which is unhappily in marked contrast to the simplicity obtained in the application of Ohm's law to conductivity, and of a similar law to capacity effects. Even when the magnetic characteristics of the materials used are well known and properly recorded, either by tabulation

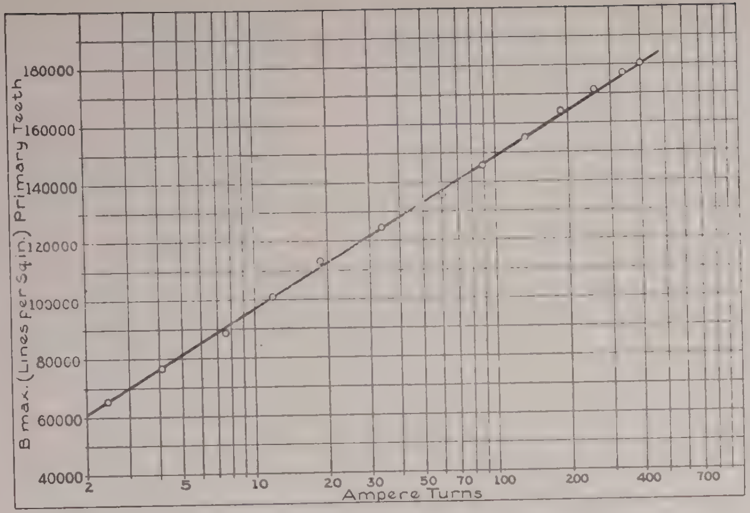


Fig. 6. 4-pole, 20-h.p. Induction Motor Magnetization Curve. Rectilinear graph carried to excessive apparent densities

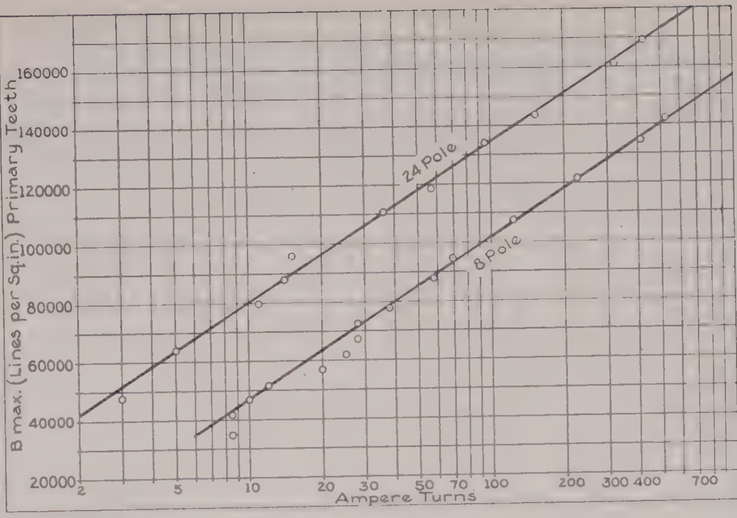


Fig. 7. 8/24-pole, Multispeed Induction Motor Graph, Showing the Effect of Modified Distribution of Density

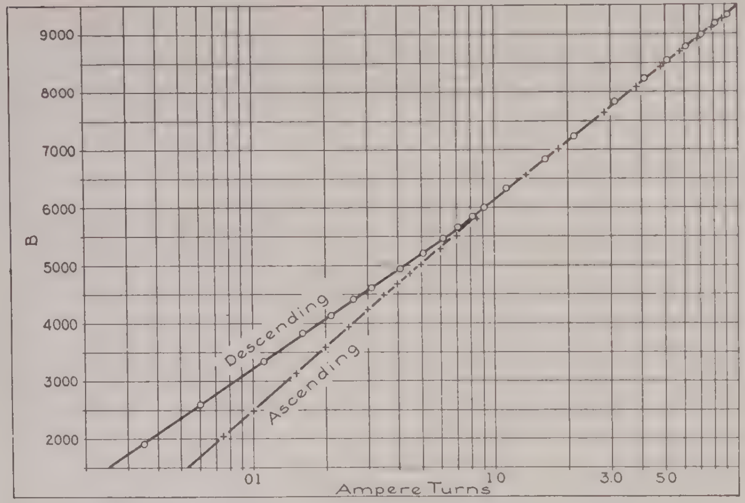


Fig. 8. Half of the Hysteresis Cycle of Permalloy, Illustrating Abnormally Low Coercive Force

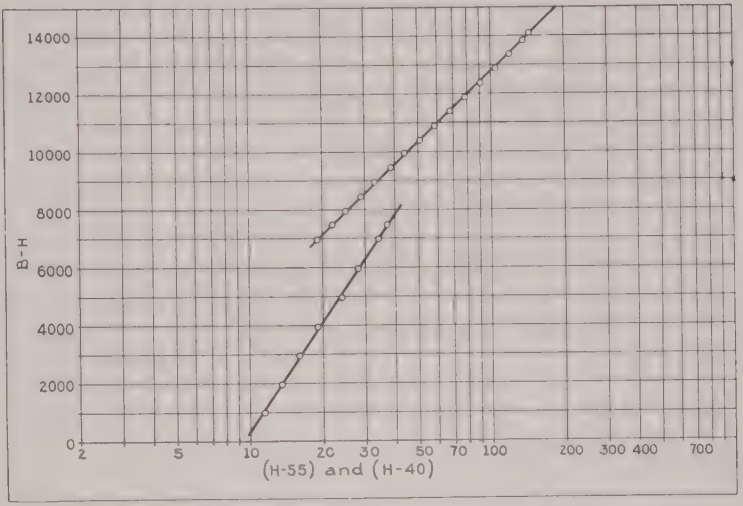


Fig. 9. Typical Ascending Branch of the Hysteresis Loop of Chrome Magnet Steel

or in graphical form, they cannot be included in even the simplest calculations without introducing assumptions and approximations which lower the accuracy and reliability of the conclusions.

Many attempts have been made to remove this handicap to some extent by means of empirical formulas, which, although not as simple as Ohm's law, would nevertheless facilitate mathematical operations. Of many such equations three recent forms may be taken as representative.

(1) The well-known equation of Kennelly has been modified by Mr. E. M. Watson so as to conform to the complete demagnetization curve of hard magnet steel. In its revised form the law may be written:

$$\frac{H+H_c}{B-H}=a+b\ (H+H_c) \qquad (4)$$

(2) Lamont's law has been generalized by Mr. S. L. Gokhale so as to represent with considerable accuracy the higher ranges of density close to saturation. If S be used to represent the saturation value of B, the equation may be written:

$$g-hH=\log\ (S-B) \qquad (5)$$

(3) M. Deri has published equations with suitable coefficients, which are applicable to the range of densities most frequently encountered in practice and which closely resemble those proposed in the present paper. The form of his equation is

$$B=c\log H \qquad (6)$$

Although it was not recognized until recently, the proposed equation $B-H=c\log\left(+\sqrt{(H\pm H_c)^2}\right)$ could be derived from Deri's by a modification very similar to that which Watson applied to the Kennelly equation. As a matter of fact it was reached in an attempt to improve the common practice of plotting $B-H$ curves on semi-log cross-section paper in order to secure an appropriately condensed scale for large values of H.

It should be recognized that any curve of an order which requires three or more constant coefficients is very flexible and by selection of suitable constants may be made to conform to any smooth curve of experimental data over a considerable arc of the curve. The successful use of an equation in this way is, therefore, no proof of the correct selection of the equation to represent the experimental facts. For such a proof one must resort to comparative analysis of the constants required. In the case of the magnetization curve the selection of the logarithmic equation requires the adoption of constants among which many interesting relations are found to exist.

The material first used for analysis consisted of a series of symmetrical hysteresis loops for standard sheet steel. The original data were not available except in a few instances and the records of the results were blueprints of the graphs. Some inconsistencies in the analysis may therefore be attributed to inaccurate plotting, but it is also probable that this steel was not so homogeneous as many others which might have been used. On many samples which seemed to be superior in this respect, the available data were much less complete.

The form of the proposed equation suggested the use of differential methods for the elimination of unknown constants. It was apparent, however, that the amount of the experimental and graphical errors introduced was too great to permit the use of the differential method. On the other hand, with the logarithmic equation a simple and convenient method of approximation by trial and error is available. The values of $B-H$ and H are first plotted on semi-log paper; $B-H$, on the uniform scale (vertically), and H on the logarithmic scale (horizontally). By noting the curvature of the graph a close estimate of the necessary correcting term can be made. An increasing convexity upwards as zero values are approached indicates that a constant term must be deducted; a corresponding concavity means that a constant must be added. The correction is then made by moving each point horizontally over an equal number of apparent units on the logarithmic scale. If this process is repeated a family of curves is obtained in which the sign of the curvature changes from positive to negative. If the relationship represented by the graphs is of the form suggested, some intermediate graph will be a straight line. By means of a straight-edge this rectilinear graph can be picked out. The apparent coordinates of any two convenient points will furnish the means of calculating two constants. The third is obtained by identifying the corrective value used in transferring the original graph to the rectilinear graph. After some practice it will usually be possible to obtain the best rectilinear graph after one or two preliminary estimates.

The coefficients obtained in this way for the sheet steel data suggest the following inferences.

(1) The constant H_c has two distinct values, about 0.5 and 0.7.

(2) These values are suitable for both ascending and descending branches of the cycle.

(3) The sign of H_c is reversed in passing from ascending to descending conditions.

(4) The smaller loops of entirely convex form require only one constant, 0.5, and this form is retained so long as $H_{max.}$ does not exceed $H_c=0.5$.

(5) When $H_{max.}$ exceeds 0.7 the portion of the descending range between $H=H_{max.}$ and $H=H_{c2}=0.7$ is represented by equations in which $H_c=0$.

(6) The sequence of values of H_c is the same for both branches. Higher values succeed lower values on both when the cycle is followed in the counter-clockwise direction.

(7) The term H_c is not obtained from the value of H for $B-H=0$, but depends on the conditions at the points of contrary flexure. It should not be confused with this value which is generally known as the "coercive force."

(8) Corresponding values of c (for equal values of H_c) are approximately constant for all descending branches of loops in a given material.

(9) The terms b for corresponding ranges are not constant, but are probably functions of the maximum values of $(B-H)$.

The form of the function mentioned in (9) was not identified. On the supposition that the number of the constants required might be due to non-homogeneous structure of this particular material, the test data of a range of very diverse materials were analyzed by similar methods. The diversity of magnetic characteristics is best indicated by the variation of the values of H_c required in each case. Thus for samples of *permalloy* values as low as $H_c=0.075$ and 0.115 were required, while hardened cobalt steel required $H_c=100$ and 150, giving a range of coercive force indicated by a ratio of about 1300 to 1. The similarity of form of the hysteresis loop over this wide range of magnetic quality is best represented by writing the equations in terms of H/H_c.

These extreme qualities of magnetic hardness and softness seem to be associated with more homogeneous structures than those occurring in materials of intermediate quality and in several samples simpler and more consistent equations were obtained. Thus, among ordinary magnet steels with an apparent coercive force of about 50, samples were found in which a single equation without change of constants represented the complete descending range of the cycle with very close conformity.

It will be noted that, if graphic records of magnetization are preferred, these will take the form of straight lines, if plotted on semi-log paper. In the absence of such records it is only necessary to remember two constants in order to complete the calculation with the aid of a common slide rule.

Some examples of semi-logarithmic graphs representing laboratory tests have been reproduced in Figs. 8 to 12 inclusive. In these and also Fig. 13, the values are plotted in c.g.s. units.

Fig. 8 represents the half of a symmetrical hysteresis cycle for a sample of *permalloy* carried to $B_{max.}=10{,}000$. The values of H_c used are as follows:

$B=1000$ to 5000	$H_c=-0.1$ ascending
$B=5000$ to 9300	$H_c=-0.15$ ascending
$B=9300$ to 5600	$H_c=+0.11$ descending
$B=5600$ to 1000	$H_c=+0.11$ descending

Fig. 9 represents the ascending branch of a symmetrical loop for a sample of chrome magnet steel ($B_{max.}=14{,}300$), and Fig. 10 represents the descending branch for a similar sample with $B_{max.}=13{,}500$. In each case the data (which were obtained from large-scale blue print graphs) were not sufficiently consistent to determine the remainder of the cycle with any degree of certainty. The values of H_c used were, for Fig. 9, $H_c=-40$, and $H_c=-55$; and for Fig. 10, $H_c=+70$.

Fig. 11 gives the data for a ring of hardened cobalt steel carried through a cycle with $B_{max.}=10{,}000$. The values of H_c used were

$B=4000$ to $10{,}000$	$H_c=-100$ ascending
$B=10{,}000$ to 5000	$H_c=+100$ descending
$B=5000$ to -4000	$H_c=+130$ descending

The second descending range furnishes a good illustration of the fact that the value of $-H$ for $B=0$ is incapable of determining a suitable parameter for a family of hysteresis cycles. This value is usually termed the coercive force and treated as if it were a basic characteristic of the material. The cases which have been analyzed indicate that, whatever type of equation may be used to represent the cycles of different maximum density, corresponding values of H will not be found at equal values of B.

Fig. 12 represents the magnetization curve of the same ring of cobalt steel carried up to a value of $B_{max.}=15{,}800$, with $H_{max.}=400$.

Unlike the previous graphs, this has been plotted on uniform cross-section paper, using $\log_{10} H$ as abscissa. This has been done in order to include for comparison the lowest portion beginning at the origin. The writer has discovered that the value of H_c obtained

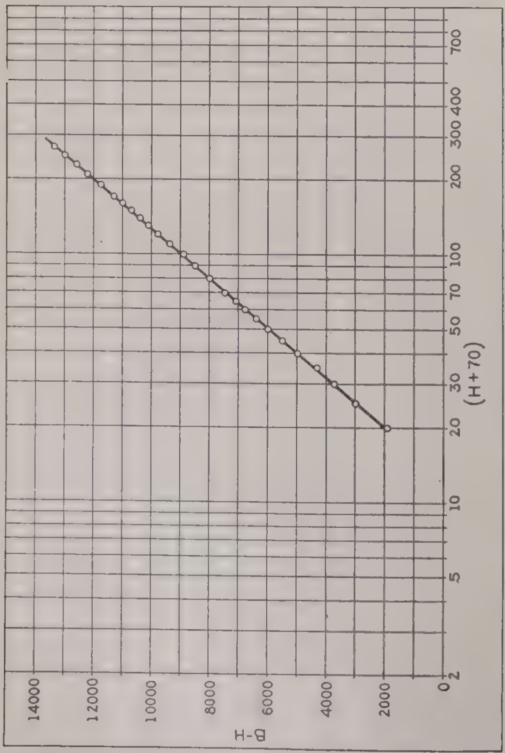


Fig. 10. Chrome Magnet Steel—Typical Descending Branch of the Hysteresis Loop, Completely Represented by a Single Equation

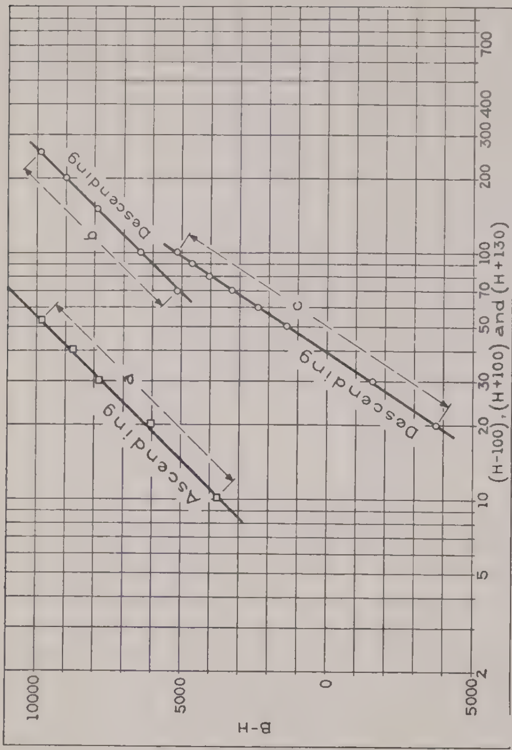


Fig. 11. Both Branches of Hysteresis Loop—Cobalt Magnet Steel (Honda Steel), Showing Abnormally High Coercive Force

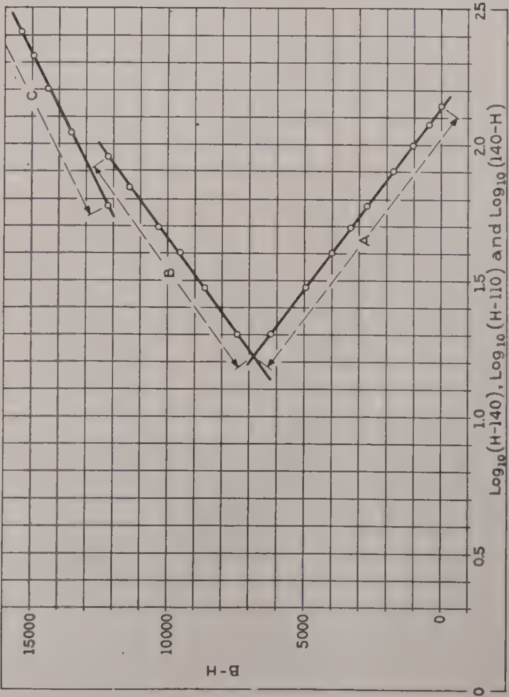


Fig. 12. Cobalt Steel Magnetization Curves, Showing Application of Logarithmic Equation to the Range of Reversed Curvature Near the Origin

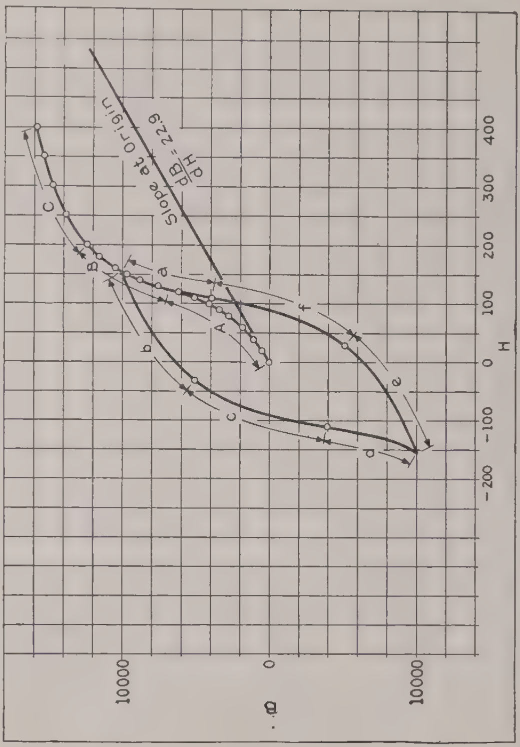


Fig. 13. Data for Cobalt Steel Given in Figs. 11 and 12, Plotted According to Conventional Methods

from the upper range of the curve may also be used to secure the best equation for the range in the vicinity of zero by the simple expedient of reversing the signs of B and H. The equations derived from the test data are as follows. $(B-H)$ is in kilolines per sq. cm.

(A) $B-H=0$ to 6.23

$$-(B-H) \qquad = 7\ 4 \log_{10}\left(1-\frac{H}{140}\right)$$

(B) $B-H=8.66$ to 12.2

$$(B-H)-13.31=7.5 \log_{10}\left(\frac{H}{110}-1\right)$$

(C) $B-H=11.42$ to 15.4

$$(B-H)-14.07=4.9 \log_{10}\left(\frac{H}{140}-1\right)$$

In comparison, the equations for the loop $B_{max.}=10{,}000$ are also given

Ascending

(a) $B-H=3.8$ to 10

$$(B-H)-12.13=8.4 \log_{10}\left(\frac{H}{100}-1\right)$$

Descending

(b) $B-H=10$ to 5

$$(B-H)-6.45=8.4 \log_{10}\left(\frac{H}{100}+1\right)$$

(c) $B-H=5$ to -3.8

$$(B-H)-6.6=12.6 \log_{10}\left(\frac{H}{130}+1\right)$$

Fig. 13 shows the usual method of plotting the data covered by Figs. 11 and 12. Corresponding letters have been used in these three plots and in the foregoing equations to identify corresponding ranges of the values of B and H.

Ranges *d*, *e*, and *f* which complete the cycle of Fig. 13 merely repeat ranges *a*, *b*, and *c* respectively with reversed signs for the values of B and H.

It is of interest to note that although the ratio $H_{c2}/H_{c1}=3/2$, which appears in a large number of cases, is not closely adhered to in this case, on the other hand this ratio appears in the relation between successive values of C.

Summary

The use of semi-log graphs for the inspection and analysis of excitation tests of induction motors is recommended. Graphs are given to demonstrate that by the use of a suitable correction coefficient H_c these can be obtained in rectilinear form, after elimination of air gap reluctance by well known methods.

These graphs also demonstrate that the redistribution of flux density due to saturation is not incompatible with the retention of the rectilinear form. The actual distribution may be treated as equivalent to a hypothetical sine distribution up to an apparent maximum density of 170,000 lines per sq. in. By the use of similar graphs, based upon laboratory test data, it is shown that an equation of the form

$$B-H=c \log\left(+\sqrt{\left(\frac{H}{H_c}\pm 1\right)^2}\right)$$

is suitable for representing the effect of magnetizing force upon strongly magnetic material whether it starts from a completely demagnetized condition, or follows an established symmetrical cycle. It is also demonstrated that the same type of equation is equally applicable to materials of the most diverse magnetic characteristics.

Conclusions

Satisfactory representation of the relations between B and H in strongly magnetic materials may be based on the following hypothesis:

The basic relation between the internal values of B and H in a homogenous, uniformly magnetized portion of highly magnetic material may be expressed by the equation $B=c \log H$.

The modifications of this equation when applied to externally measurable values of B and H are due to the fact that the latter represent only net surplus values. The externally impressed m.m.f. is subject to modification by the internal m.m.f., and the internal flux density at any point is the resultant of the external flux together with certain internal fluxes existing in short-circuited paths.

No explanation of the basic logarithmic relation is advanced at the present time. It is merely presented as a concise statement of the facts to which any proposed hypothesis must conform.

If the equation can be confirmed as the expression of a rigorous physical law, its form would not be without precedent. For example, it is the form taken by Fechner's law of stimulus and sensation. Perhaps the most demonstrable case of the relation is in the field of sound. The sensation of pitch testifies to the equality of two different octave intervals, whereas the science of sound testifies to the equality of vibration frequency ratios. Stimuli in geometric progression cause sensations in arithmetic progression, and the relation of the latter to the former is logarithmic.

A Modern Industrial Power Plant

By A. R. Smith

Construction Engineering Department, General Electric Company

The great central stations of the public utility companies are ordinarily called upon to furnish electric power only, so that it is relatively a simple matter to design such stations with adequate architectural arrangements for future generating units. With the privately owned station built to serve a large manufacturing plant the problem is more complicated. The requirement may be more for live steam for heating and for industrial processes than for electric power. Progress in manufacturing methods may introduce new and unforeseen demands upon the power plant. These things make it difficult to determine just what direction the design of the plant should take. In the accompanying article Mr. Smith describes the power station recently erected at the Erie Works of the General Electric Company, an example of the most advanced practice in its field.—Editor.

The construction of a permanent power plant at the Erie Works of the General Electric Company, located at Erie, Pa., was delayed for nine years following the initial factory development because the light, heat and power demand at that time was so small compared with the expected ultimate demand that it was uneconomical to attempt the construction of a permanent power plant. The first section of the permanent plant, erected in 1919, consisted of one-half of the ultimate boiler room. Five years later, in 1924, the boiler room was extended and the first permanent stack was erected.

This plant is located at approximately the center of the Works plot. It is about one mile from the shore of Lake Erie and 90 feet above the lake level. A central position rather than a lakeside site was selected because the principal service which this plant must render is that of supplying industrial steam, heating steam and turbine-testing steam. The electric power produced is largely a by-product from the heating steam.

Steam Generation

Boiler room development at Erie is comparable to boiler rooms of large public utility power plants. The present boiler room capacity totals 5600 rated boiler horsepower, which is capable of developing 15,000 boiler horsepower or producing 450,000 pounds of steam per hour with all boilers in service. The ultimate capacity, based on the expected ultimate development of the Works, will be 1,500,000 pounds of steam with all boilers in service. If all this steam were used for producing electric power, the capacity of the plant would be approximately 135,000 kilowatts.

The boiler just installed is rated at 2000 horse power at 250 pounds steam pressure and will deliver steam with a superheat varying from 150 deg. to 200 deg. F. The boiler is of the latest B & W cross drum type, with 20-ft. tubes 20 rows high. The boiler is set 20 ft. above the floor and over a 14-retort, 29-tuyere underfeed Taylor stoker. The stoker will be supplied with preheated air, heated by the exhaust steam from the turbines.

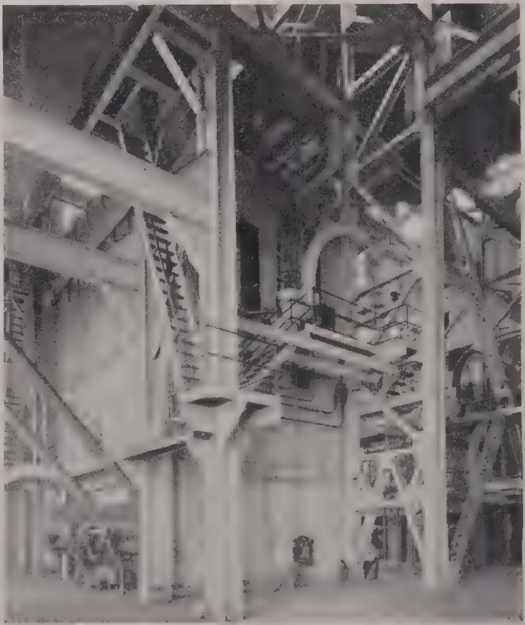


Fig. 1. A General View of the Boiler Room of the Erie Works Power Plant, Showing the Latest Installation of a 2000-h.p. B & W Boiler

The new stack will serve 6 such boilers or their equivalent in capacity. Measured from the floor of the firing aisle it is 300 ft. high and has an inside diameter of 18 ft. at the top. The stack is made of steel resting on the building frame, and is lined from bottom to top with firebrick. At the base of the stack and below its supports is a large soot hopper, containing eliminators for catching cinders,

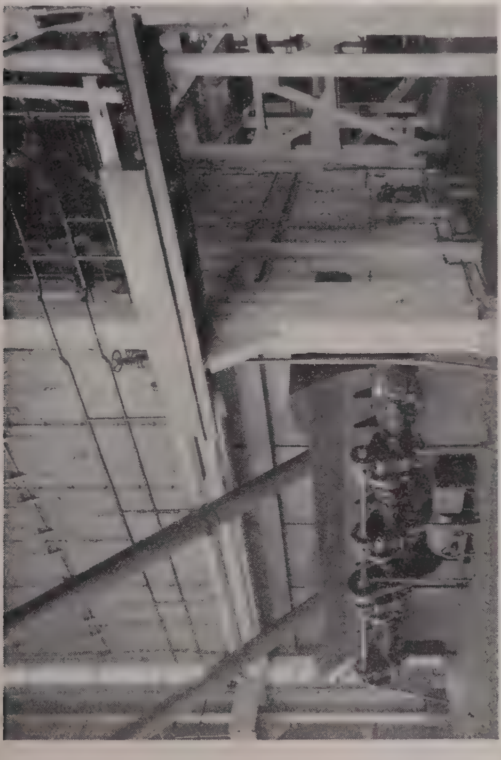


Fig. 2. The Taylor Stoker, with Mechanically-operated Swinging Coal Spouts

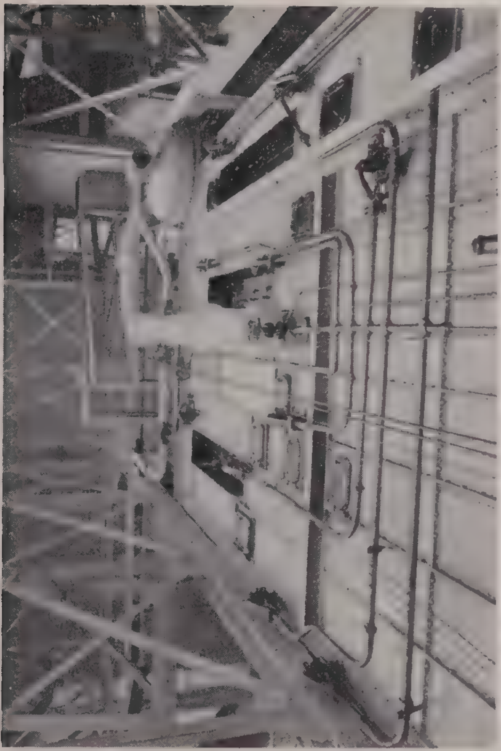


Fig. 3. Looking Up the Face of the Boiler from the Fire Room Floor

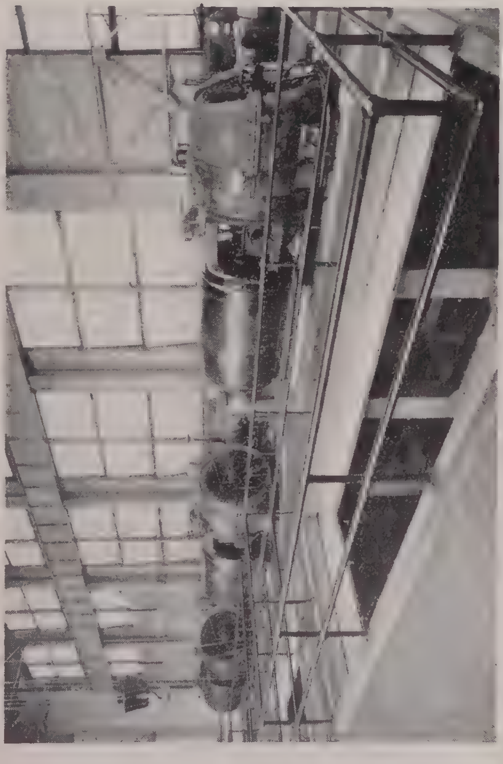


Fig. 4. Main Generating Platform. The further generator is operated non-condensing and its exhaust steam used for plant heating

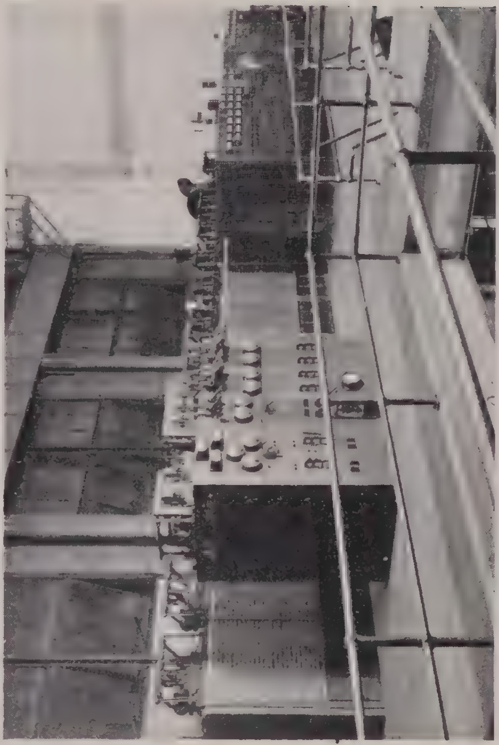


Fig. 5. Switchboard Installation with 11,000-volt Oil Switches in the Rear

soot and coke, which ordinarily are driven out through the stack.

Turbines and Piping

Two of the three 2500-kw. turbine units are condensing, with provision for full extraction; the third is non-condensing for use exclusively with the heating system. The back pressure on the heating system does not exceed five pounds. This pressure is materially reduced in moderate weather. These turbines can deliver to the heating system 275,000 pounds of steam per hour, which is one-half of the ultimate demand. The maximum heating demand for the plant is for such a short period of time that it is not practicable to attempt to extract by-product energy, or to install exhaust steam mains large enough to carry the peak heating load. In this plant the exhaust steam pipes leading to the various factory buildings are made large enough to serve the average heating demands, and the peak demands are taken care of by bleeding high pressure steam into the heating system in each of the principal buildings. When the electrical load is insufficient to supply exhaust steam for heating, high pressure steam is bled through nozzles into the exhaust main at the power house.

Congestion in steam tunnels in other plants of the Company emphasized the necessity of a liberal design at Erie. The steam tunnel leaving the power plant is 14 feet high and 14 feet wide; this runs to the central avenue where it branches east and west, the cross-sectional size of the tunnel being reduced at the far ends where the pipes are smaller. This is the first adequate industrial plant steam tunnel that the writer has seen. It provides for a liberal increase in capacity and affords every facility for the proper maintenance of pipe lines and covering.

Electrical Equipment

The turbine room also serves as an electrical distribution center. The 11,000-volt circuits are fed to four transformer and two motor-generator stations distributed throughout the Works so that each serves an area of about 800 feet square. In these substations the high voltage is transformed to 600 volts for power or 230/150 volts for light, or is converted to 500/250 volts direct current with grounded neutral. Direct current is used only for variable speed motors which drive machine tools. Two of these substations are for generating direct current, and each contains a 1000-kw. motor-generator set. There is a similar unit in the power plant, which is connected to the direct-current system so that it will serve as a spare unit for any disabled set and will supply direct current during nights and Sundays.

All electrical distribution is underground. The conduit system and splicing chambers have been most carefully designed so as to avoid the spread of trouble and to give a maximum heat conduction into the ground. Where the main conduit system crosses the steam tunnel, special provisions were made in providing heat insulation and proper air circulation so that the heat from the tunnel and the heat from the cables are dissipated independently. This is probably the first attempt at a flexible cable conduit system at any power plant. The ducts terminate in a cable basement so that it is possible to interchange circuits and switches to meet unusual factory requirements.

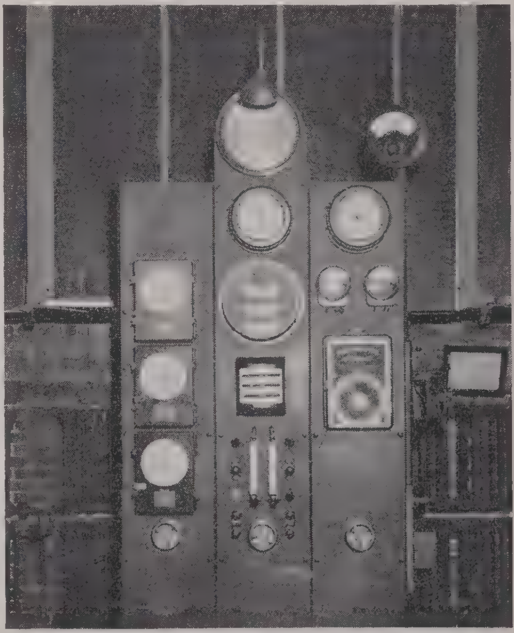


Fig. 6. Boiler Room Control Panel. In the center is a new type of 3-scale meter which shows coal flow, air flow and steam flow, and gives at a glance all the information necessary to operate the boiler at highest efficiency

The development of a manufacturing plant often covers a period of many years and even though the factory plant may be practically completed within a few years, manufacturing developments will materially change the demands on the power house. The rapid development of power plant apparatus is still another factor, which prevents the fixation of conditions. Past experience with repeated changes and additions within manufacturing power plants has shown the advisability of a liberal design in early installations, which will permit not only a decided increase in the capacity of any of the services, but which will also permit the employment of the latest apparatus and methods at the time extensions or changes are made. The Erie power plant was developed with this fundamental idea in view. It was built as much for the future as for the existing or immediate demands.

The Parallel Operation of Alexanderson High-frequency Alternators

By J. L. Finch

Engineering Department, Radio Corporation of America

In radio communication as in power generation, transmission, and distribution, the reduction of promising experimental phenomena to commercial practice leaves behind a history of developmental problems solved. While there is a qualitative similarity between the electrical factors encountered by the radio engineer and those met by the power engineer, there is usually so great a quantitative difference as to put quite a different face on the problems of each of these engineers. One example occurs in the case of the parallel operation of alternators where on the one hand machines of 25- or 60-cycle frequency are to be run in harmony on a comparatively constant load, and on the other hand machines of 15,000 to 30,000 cycles are to share satisfactorily a load that rapidly fluctuates between zero and full value. The following article describes how the latter problem was solved.—Editor.

In the successful development of commercial radio communication using high-frequency alternators, the problem of parallel operation of these machines presented itself and has been satisfactorily solved. The difficulties involved and their solution are matters of importance to radio engineers, and may doubtless be of interest to power engineers as well.

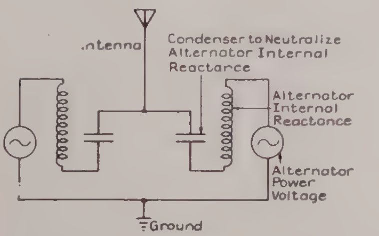

.ntenna
Condenser to Neutralize Alternator Internal Reactance
Alternator Internal Reactance
Alternator Power Voltage
Ground

Fig. 1. Method of Partially Neutralizing the Internal Reactance of Alternators for Parallel Operation

The operating frequency of the alternators which have been used in parallel for radio communication ranges from 15,000 to 30,000 cycles per second. This high frequency in itself does not seem to present any special problems in parallel operation. However, the type of machine required to generate such frequencies must necessarily have an excessively high internal reactance and also a high resistance, and these features do introduce special problems. The high internal reactance makes necessary the provision of means for partially neutralizing this reactance in order to obtain sufficient circulating current between the two machines to produce the required synchronizing torque. This partial neutralizing can very easily be accomplished by placing a condenser bank of the proper rating in series with the alternators ahead of the paralleling connection, as shown in Fig. 1. Without such condensers, the circulating current will attain a maximum of only about 35 per cent of full-load current, and a power interchange of only about 10 per cent of full-load power at the most critical angle. When the condensers are used and adjustment is made for the highest possible power interchange, its value at the most critical angle is about twice full-load power. This is not a practical operating condition since the interchange power is all absorbed in the internal resistance of the alternators themselves. In other words, the load on the driving motor of the lagging machine is not decreased at all but the load on the motor of the leading machine is increased by four times the rated power output.

On the other hand, the problem of parallel operation is greatly simplified in this case due to the fact that the load on the two machines can be kept equal and that the driving motors may be paralleled, to assure equal motor input. Thus the synchronizing energy required to keep the alternators in step is reduced to a minimum.

These high-frequency alternators are driven by wound-rotor induction motors having external secondary resistance. The voltage applied to the motors is controlled by means of iron-core inductance coils in series with the motor primaries. The reactance of these coils can be varied by saturating the iron cores with direct current, in a separate winding. The speed of the machine is held constant to within one-tenth of one per cent through the control of the motor voltage by an automatic device. The tendency for the speed to change due to the telegraphic keying is minimized by using a set of compensating relays controlled with the telegraphic signals which cut in and out sufficient secondary resistance to compensate for the change in load. The motors can be held in synchronism by paralleling their secondary circuits and the voltage on the two motors is kept equal by paralleling their primaries so the power input to the two is very nearly equalized for all conditions.

When the alternators are parallel there is a decided tendency for hunting between them, as is the case under certain conditions with synchronous machines at power frequencies. There seem to be many conditions which tend to produce hunting in the case of high-frequency alternators under telegraphic load, and they seem to vary with the individual installations and even to change frequently in the same installation. The latter is probably due to certain variations in the power supply, such as might be caused by the changing of power generator units, etc.

One cause for hunting seems to originate in the driving motors when their secondaries are paralleled directly and is probably due to certain torque harmonics which do not coincide in the two motors. This source of trouble was largely eliminated by placing fixed resistances in the motor secondary circuits between the paralleling connection and the secondary windings, as shown in Fig. 2 at *R*. In this manner the advantage of separate resistances was partially obtained, while still maintaining the advantage of having any adjustments in the secondary resistance affect the two machines alike.

A second source of variations that cause hunting is found in the telegraphic keying. The keying is usually controlled automatically so that the impulses recur with great regularity. Since the motor input and the alternator output cannot be exactly balanced under both of these widely different conditions of load, a tendency to hunt is produced; and when the keying speed corresponds to the period of the hunting between the alternators, the hunting will tend to build up and the alternators would drop out of step if no corrective measures were taken. Even though the input and output powers were exactly balanced, any initial hunting would have a tendency to increase under favorable conditions as can be shown. For instance, if the antenna were not in exact resonance with the alternators the power would not be delivered at unity power-factor. Then while the machines were not exactly in phase one alternator would be loaded more heavily than the other. If the lagging machine happened to be the one more heavily loaded, then it would tend to lag still more. With a constant load this tendency would be neutralized during the other half of the hunting cycle, but under telegraphic load with the keying at the critical speed the load is removed very frequently during this half cycle so the hunting tends to build up.

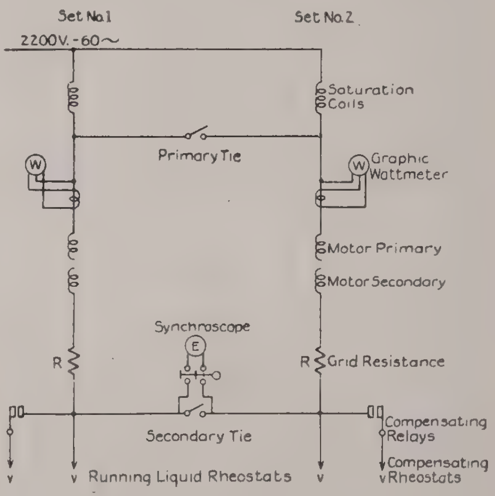


Fig. 2. One-line Diagram of Motor Paralleling Circuit

Similarly, any initial hunting would tend to increase under favorable conditions of keying due to the fact that the synchronizing torque is not the same with the key open as with the key closed, either with or without the antenna load. On account of this the torque drawing the machines back into step might be greater each time than that restraining them from going out of step in the opposite direction, thus causing an increase in hunting.

A third source of hunting is found in any irregularity of the alternators themselves, due to inexact spacing of the poles in the rotor or in an irregularity in the field flux that the rotor passes through. Such irregularities cannot be entirely eliminated in machines with such a large number of poles as are required to produce these high frequencies. (These machines have from 772 to 1220 poles.) Thus the load may vary with rotor position and hunting may result if the hunting period corresponds to the alternator revolutions.

Hunting from the second and third sources was largely eliminated by adjusting the synchronizing torque to such a value that the hunting period was lower than that which would correspond to the lowest keying speeds used in practical operation. This period was also lower than that corresponding to the alternator revolutions.

After all of these measures were taken it was still found that under some conditions hunting became serious. It was obviously impossible to provide the equivalent of pole-face windings commonly used in synchronous machines at power frequencies to dampen out hunting, so an entirely new method had to be developed. Owing to the fact that the mean power interchange between the two alternators is essentially zero when properly balanced, it is possible to use a method not practical in machines used for ordinary power purposes. In connection with this device there is placed in the tie between the two alternators an inductor (*r*, Fig. 3) which can be short-circuited by a relay (*p*). The value of the condensers in the circuit is such that with this relay closed the power interchange between the two machines at the most critical phase angle is about 25 per cent of the full-load power of either machine while with the relay open it is about half of this value. This relay is controlled in such a way that it will remain closed while no hunting is being experienced and during hunting while the phase angle between the alternators is increasing, thus giving the higher value of synchronizing torque. While this phase angle is decreasing the relay opens and remains open giving the lower value of torque until it passes through zero at which time it closes again. This has the effect of damping out hunting very rapidly.

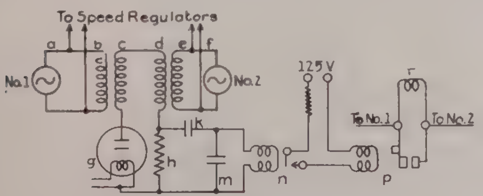


Fig. 3. Anti-hunting Device Circuit

The action is produced by the circuit shown in Fig. 3. Armature coils *a* and *f* are segregated from alternators No. 1 and No. 2 respectively (each alternator having 64 such coils) and coupled through transformers *bc* and *de* to a circuit containing a rectifier *g* and a resistance *h*. The phase of these transformers is such that when the alternators are in phase their voltages will neutralize each other. If the alternators go out of phase a resultant voltage will be produced which will cause a rectified current to flow through rectifier *g* and resistance *h* producing a voltage drop across *h*. While this voltage drop is increasing in value condenser *k* will be charged by the current flowing through the polarized relay *n*. This relay is biased so it will remain closed with zero current. The current flowing into condenser *k* will hold relay *n* closed. When the phase angle has reached a maximum and begins to decrease, the voltage across *h* will decrease and condenser *k* will be discharged through relay *n* and cause it to open. Relay *n* controls relay *p* which is the relay that was previously mentioned as acting to short-circuit the inductor *r* in the tie circuit between the two alternators. It happens that one armature coil is already segregated from each alternator for controlling the speed regulator circuits. These same coils are used for the anti-hunting device circuit.

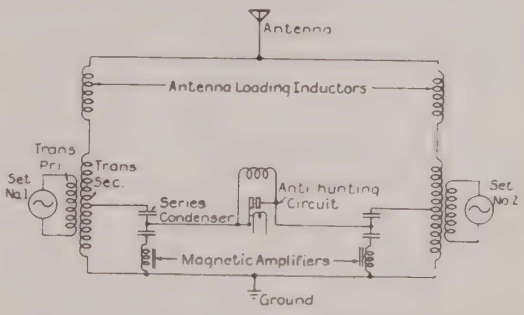
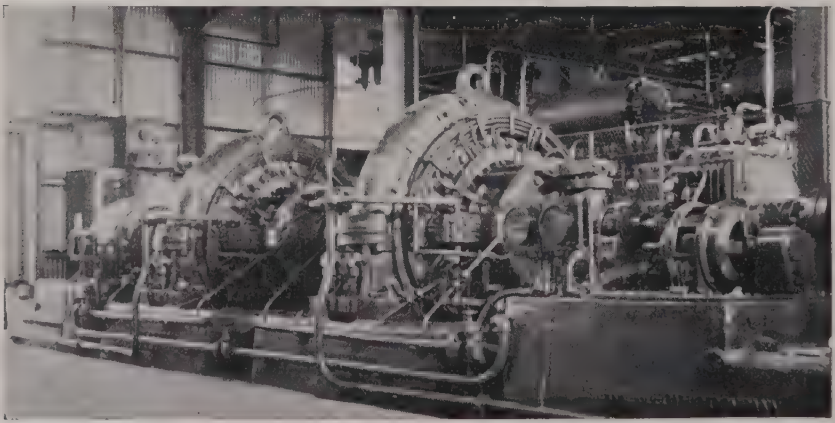


Fig. 4. Schematic Circuit for Parallel Operation of Two Alternators

In practice, the keying of the two alternator outputs introduces additional difficulties. The keying is effected by means of a device known as the Magnetic Amplifier which reduces the alternator voltage to a low value when the key is opened. This device is essentially an iron-core inductor shunted across a section of the alternator secondary winding. In the key-open condition, the iron core of this inductor is saturated with direct current which reduces its reactance to a low value. The remainder of its reactance plus the leakage reactance of the transformer winding is neutralized by a fixed condenser in series with it. Thus it forms an effective short circuit to the alternator voltage. It will be seen that, with such a condition, if the alternators were paralleled directly there would be practically zero synchronizing torque while the telegraph key was open. Fortunately it has been found practical to make the tie connection between the two alternators so as to include only that section of the alternator which the magnetic amplifier short-circuits. This circuit is shown in Fig. 4. A part of the series condensers in the magnetic amplifier circuits serves to neutralize the inductance of the alternator tie circuit so as to give the proper synchronizing torque. It so happens that the synchronizing torque is nearly the same with the magnetic amplifiers saturated as with them unsaturated, so it is maintained at a suitable value at all times. With this method of paralleling it is not permissible to connect the output terminals of the alternators directly together since such a connection would allow circulating currents to flow and neutralize the effect of the current in the tie circuit. It is therefore necessary to connect each alternator to the antenna through a separate antenna loading inductor which serves to keep such circulating currents at a negligible value. The use of this circuit eliminates the necessity for considerable extra apparatus for parallel operation only.

A unique feature of this paralleling arrangement is the lack of any need to synchronize the alternators before closing the tie switch. This switch is closed regardless of the phase relation, and since the maximum current is less than full-load current value no harm is done. The resulting hunting is quickly damped out by the anti-hunting device.

At the present time the necessary arrangements are provided for the parallel operation of the high-frequency alternator equipments installed in high-power radio stations in America, Poland, and Sweden and satisfactory operation is maintained in this manner when desired.



Two Alexanderson High-frequency Alternator Sets at Radio Central, Long Island, which are successfully operated in electrical parallel by the method described in the foregoing article

A Two-speed, Salient-pole Synchronous Motor

By R. W. Wieseman

Alternating-current Engineering Department, General Electric Company

Where a single and unvarying speed is desired, regardless of changes in load, the synchronous motor has never had a rival. Just because of this synchronous feature of operation, however, the conventional synchronous motor is not readily applied to multi-speed drives, except by changing the frequency of the power supply, which in most cases is impracticable. There are many applications where a choice of two speeds is all that is needed and to render the synchronous machine available for this class of work, the author has devised a motor with field poles of special design, and with rotor windings arranged for two methods of connection. The article describing this motor, which we here present, is reprinted from the *A.I.E.E. Journal* of April, 1925.
—Editor.

Introduction

The ordinary synchronous motor is inherently a one-speed machine because its revolving field, which is excited by direct-current, must rotate in exact synchronism with the gliding magnetomotive force of the stator. Induction motors can be built to operate at two, three, and four speeds because the induction motor has a cylindrical rotor, a uniform air gap, and a distributed rotor winding. These features make it easy to change the synchronous speed by regrouping the stator and the rotor coils. In the synchronous motor with the usual salient-pole construction, the air gap is not uniform and the field winding is concentrated. Therefore, to operate a salient-pole synchronous motor from a constant-frequency supply at more than one synchronous speed, a special design is necessary. Such a motor is particularly suitable for constant-torque loads because synchronous motors are most efficient when operated at normal magnetic flux and current densities at either speed.

The multi-speed synchronous motor can operate at unity power-factor (or at any desired leading power-factor), whereas the multi-speed induction motor usually has a rather low lagging power-factor at the lower speed, unless a special compensating arrangement is used. It will be seen later that the particular two-speed synchronous motor described has an efficiency of 95.6 per cent when operating at 5000 h.p., 600 r.p.m., and at 2500 h.p., 300 r.p.m. It can thus be seen that the possibility of obtaining two speeds from synchronous motors opens a new field of application which so far has been covered by induction motors.

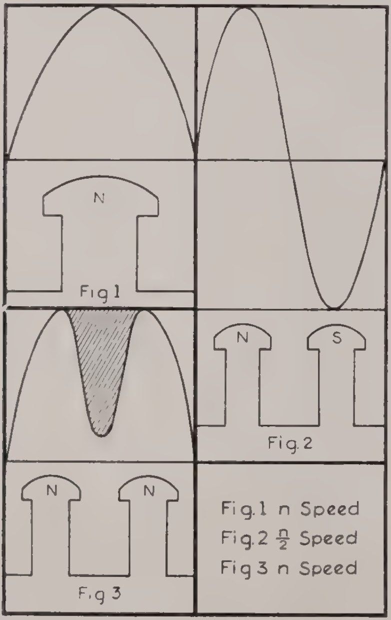
The particular motor described in this article was built to drive an alternating-current generator at two speeds in order to obtain two frequencies. This motor can function equally well as a two-frequency generator when driven at constant speed. Thus a frequency converter set, consisting of two of these machines, could supply three different frequencies.

In some mine fan installations the full capacity of the fan is not required at certain periods. In cases where a speed ratio of 1:2 is satisfactory, the two-speed synchronous motor should be suitable. Although this load would not be a constant-torque load, the efficiency at both speeds could probably be made higher than that of a corresponding two-speed induction motor. Furthermore, the synchronous motor could be operated at any power-factor to obtain power-factor correction. Thus, at the one-half speed condition only about one-eighth power is required and the remaining synchronous motor capacity can be utilized for power-factor correction. One difficulty in this application is that 100 per cent pull-in torque is required which necessitates a heavy starting winding. The ordinary starting winding can be used if a clutch is installed or if the motor is equipped with a rotating frame (super-synchronous motor).

Synchronous motors are now being used for ship propulsion. Changes in motor speed are accomplished by changing the generator frequency by varying the turbine speed. With a two-speed motor, half speed can be obtained at normal frequency. The advantage of this scheme lies in the operation of the steam turbine at normal speed where the efficiency is maximum.

Backwater conditions at certain water-power plants are such that the effective head is much less (sometimes one-half) during the rainy season than during the dry season. For efficient operation the water turbine speed should be reduced with the head, a condition which gives a much lower turbine speed during the rainy season. In cases where the turbine speed is reduced to one-half, a two-speed generator would give normal frequency at both normal speed and one-half normal speed of the turbine.

It was originally hoped that the two-speed synchronous motor could be used advantageously for refrigeration. In the summer the ammonia compressors are usually worked continuously at full capacity. In the winter the compressors are unloaded (two-cylinder compressor operated with only one cylinder), a condition which requires abnormally large flywheels. Otherwise, trouble due to hunting and excessive current pulsations will be experienced. This difficulty is now being overcome by using the modern clearance pockets in the cylinder of the compressor. With a two-speed motor both cylinders could be used at one-half speed which would give the same degree of refrigeration as at full speed with only one cylinder; but about five times the normal speed flywheel effect is necessary to prevent excessive current pulsations. Thus the flywheel for this condition is nearly as large as the one required when the compressor is unloaded, and the advantage of the two-speed synchronous motor in this case is not so marked.

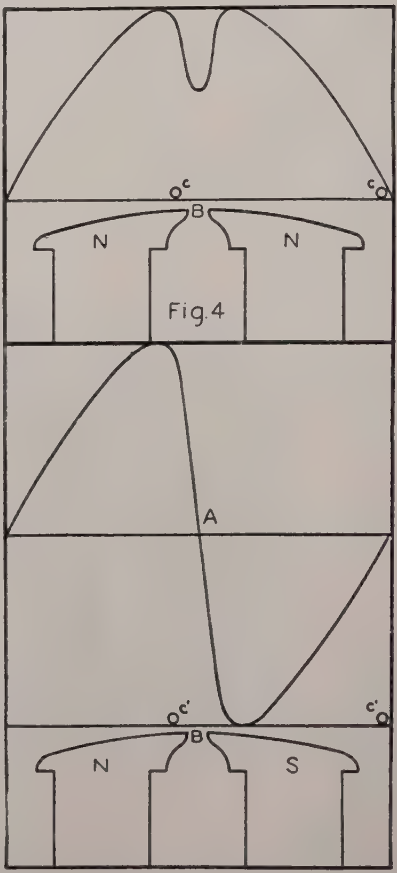


Figs. 1 and 2. Flux Distribution in the Air Gap of an Ordinary Salient-pole Machine at No Load

Fig. 3. Flux Distribution in the Air Gap of an Ordinary Salient-pole Machine at No Load When One Pole is Reversed

Special Pole Necessary for Two-speed Operation

Fig. 1 shows diagrammatically the flux distribution in the air gap over a pole-pitch in an ordinary salient-pole synchronous motor. In order to make this machine operate at half of its normal speed, the number of poles must be doubled and the armature winding must be reconnected accordingly. Thus, to have a motor which will operate at normal and one-half normal speed, it is necessary to arrange the armature and field windings so that they can be connected for either normal or twice normal number of poles. Fig. 2 shows the flux distribution in the air gap over two poles of opposite polarity which are placed in the same space as that shown in Fig. 1. This represents at one-half speed the flux distribution, which is the same as in an ordinary machine. Now, to operate this machine (Fig. 2) at normal speed, the polarity



Figs. 4 and 5. Flux Distribution in the Air Gap o a Salient-pole Machine at No Load with Special Poles, at the High and Low Speeds Respectively

of one of the poles must be reversed; the flux distribution will then take the form shown in Fig. 3. This condition gives a flux wave with a pronounced third harmonic which gives a very high core loss due to excessive hysteresis. Furthermore, the flux represented by the shaded area is lost and thus the capacity of the machine is decreased.

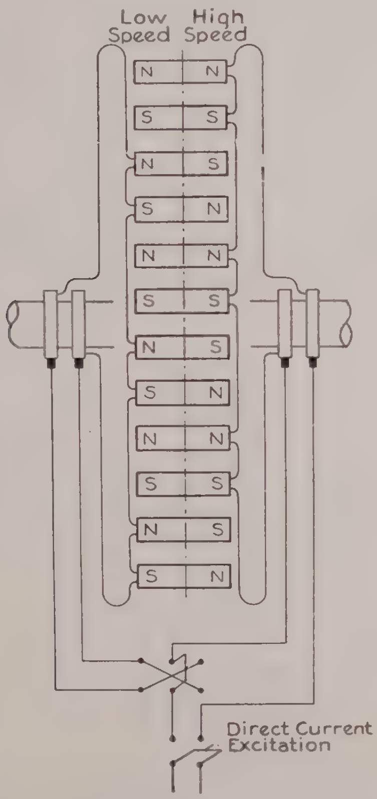


Fig. 6. Method of Changing Poles on the Rotor of a Two-speed Synchronous Motor

To overcome the objectionable condition shown in Fig. 3, the author devised a special pole piece. Figs. 4 and 5 show the flux distribution in the air gap with this special pole shape for the high and low speeds respectively. Comparing the flux wave of Fig. 4 with that of Fig 3, it will be apparent that the core loss will be much less for the flux distribution represented by Fig. 4. Tests have shown that, with the special pole (Fig. 4) at normal speed, the core loss is only 15 per cent greater than that of the ordinary salient-pole machine (Fig. 1); but this is not objectionable. At half speed (Fig. 5) this special pole increases the core loss over that shown in Fig. 2. The hysteresis loss is the same in both cases, but the eddy-current loss is greater due to the steep wave front at *A*. Tests show, however, that the core loss for the half-speed condition (Fig. 5), is also only about 15 per cent greater than that of an ordinary salient-pole machine (Fig 2). The distance between the poles *B* should be made large enough to prevent a high leakage flux for the low speed condition (Fig. 5). This leakage flux would be high only in a machine with a very large number of narrow poles. The shape of the pole face is a compromise between the best shapes required at the two speeds respectively. If the motor is to operate most of the time at the high speed, the distance between the pole pieces *B* (Fig. 4) should be made relatively small. Conversely, if the motor is to operate mostly at the low speed, the distance *B* should be increased.

Scheme for Changing Number of Rotor Poles

The scheme for changing the number of effective rotor poles in the ratio of two to one is shown by Fig. 6. The polarity of the polar projections for the high speed is indicated by *N*, *S*, *S*, *N*, etc., to the right of the vertical center line and the polarity for the low speed is indicated by *N*, *S*, *N*, *S*, etc., to the left of the vertical center line. To simplify the method of connecting the field coils, half of the coils have their connections made on one end of the rotor and the other half are connected on the opposite end. It should be noted that every other pair of polar projections have the same polarity for both the high- and low-speed conditions and the field coils on these polar projections are connected to one set of collector rings—to the right. The pairs of polar projections whose polarities must be reversed when changing from the high to the low speed, or vice versa, are connected to the other set of collector rings—to the left. The two sets of collector rings are connected in series through a reversing switch. The number of rotor poles is changed in the ratio one to two—high to low speed, or vice versa, by throwing the reversing switch to the right or to the left.

Description of Stator

The stator of a two-speed synchronous motor is practically the same as the stator of an ordinary synchronous motor. The stator frame and stator punchings are exactly the same. No special arrangement of the turns or the conductors in the coil is necessary. The only difference is in the stator coils and coil connections. The coils usually have a smaller pitch than those used on ordinary synchronous machines and thus the coil and projection is less. The stator coil pitch can be varied within certain limits to accommodate the conditions of design. At the high-speed connection the coil pitch can be made 50 to 60 per cent (coil *c c*, Fig. 4), which makes the pitch 100 to 120 per cent (coil *c′ c′*, Fig. 5) at the low-speed connection.

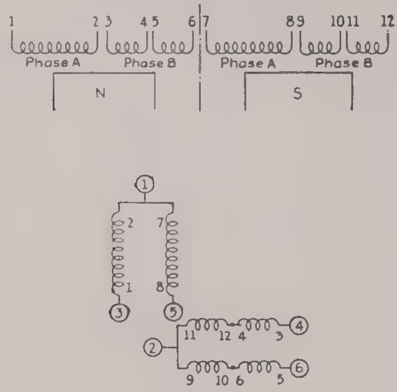


Fig. 7. Two-phase Stator Winding—90-deg. Phase Belt
P-poles N-speed
E-voltage Two Circuits
Lines 1 and 3, 2 and 4
Connect 3 to 5, 4 to 6

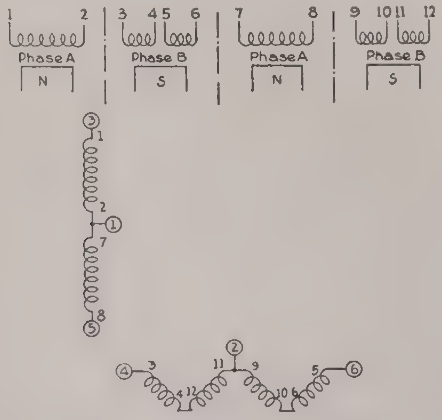


Fig. 8. Two-phase Stator Winding—180-deg. Phase Belt
2P-poles N/2-speed
E-voltage One Circuit
Lines 3 and 5, 4 and 6

Alternating-current motors are usually supplied with electric power from constant potential lines. Since it is desirable to have the magnetic flux density in the air gap approximately the same at both speeds, it follows that the number of turns in series per phase of the stator winding at low speed must be twice the number in series at high speed. Therefore, changing the number of stator poles in the ratio of one to two consists of changing the number of circuits in the ratio of two to one in such a manner that half of the phase groups are reversed. The method of reconnecting one phase of the stator winding by reversing every other phase group is similar to reconnecting the field coils as shown in Fig. 6.

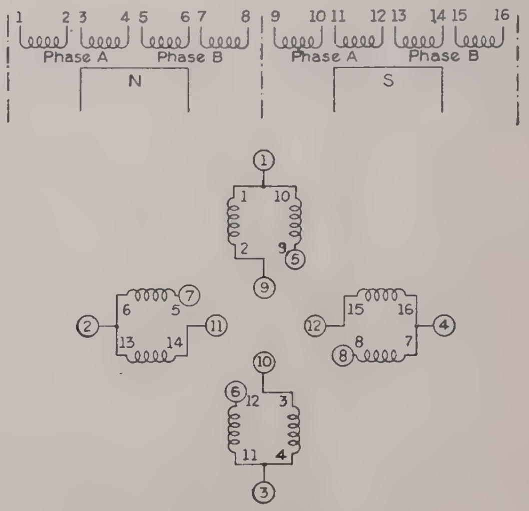


Fig. 9. Two-phase Stator Winding—90-deg. Phase Belt
P-poles N-speed
E-voltage Two Circuits
Lines 1 and 3, 2 and 4
Connect 5-6-9-10
7-8-11-12

Two-phase Stator Windings

Figs. 7 and 8 show the method of connecting a two-phase stator winding for the high- and low-speeds respectively. This connection requires only six terminals and it can be used for either three- or four-wire two-phase. The advantage of this connection is its simplicity. For this reason it is used on induction motors. Its disadvantage is that the phase belt is 180 deg. at the low-speed condition. A 180-deg. phase belt is not recommended for a two-speed synchronous motor because the short-circuit core loss with a 180-deg. phase belt is nearly twice that obtained when the phase belt is 90 deg. Furthermore, the flux per pole is 41 per cent greater with the 180-deg. phase belt, and thus the core loss is about 90 per cent greater and the field $I^2 R$ loss about 250 per cent greater.

To overcome the objectionable features of the 180-deg. phase belt at the low-speed condition, a 90-deg. phase belt should be used and the stator winding connected as shown in Figs. 9 and 10. In Fig. 9, each phase is split into two 45-deg. belts, which become 90-deg. belts in Fig. 10. Twelve terminals are required when the two-phase power supply is three-wire. If the power supply is four-wire, the leads *9*, *10*, *11*, and *12* (Figs. 9 and 10), can be connected internally and then only eight terminals are necessary. In this case the line terminals for the high speed, Fig. 9, will be *1-3*, *2-4*, and the leads *5*, *6*, *7*, and *8* are connected. For the low speed, Fig. 10, the lines will be *5-7*, *6-8*, and no connection will be necessary.

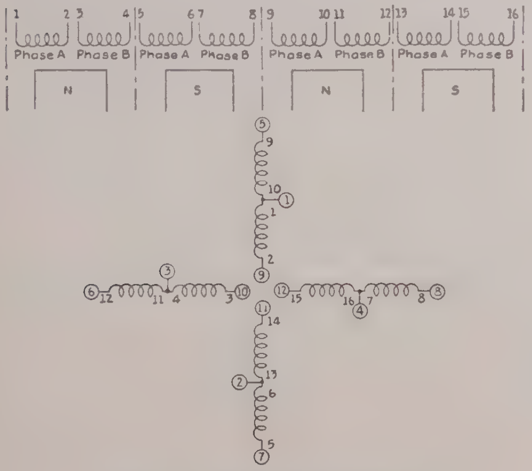


Fig. 10. Two-phase Stator Winding—
90-deg. Phase Belt
2P-poles N/2-speed
E-voltage One Circuit
Lines 5 and 7, 6 and 8
Connect 9 to 11, 10 to 12

Three-phase Stator Winding

Figs. 11 and 12 show the wiring diagrams for a three-phase stator winding which requires only six terminals. The phase belt for the high-speed condition is 60 deg. and for the low-speed condition 120 deg. The increase in the phase belt from 60 deg. to 120 deg. helps to counteract the decrease in flux due to the increase of the stator coil pitch when changing from high to low speed.

A 5000/2500-h.p., 600/300-r.p.m., Two-speed Synchronous Motor

Fig. 13 shows the stator of a 5000/2500-h.p., 600/300-r.p.m., 12/24-pole, 60-cycle, unity power-factor, two-phase, 2300-volt, two-speed synchronous motor with the end shields removed. The stator winding is arranged so that a 90-deg. phase belt is obtained at both speeds.

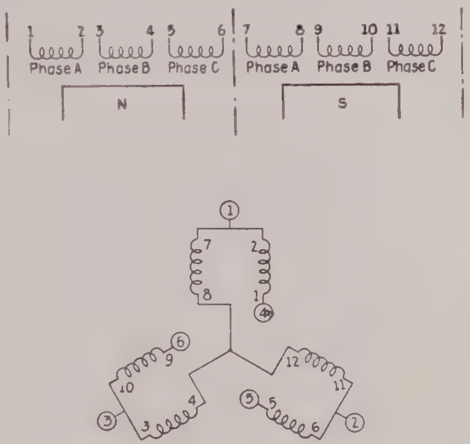


Fig. 11. Three-phase Stator Winding—
60-deg. Phase Belt
F-poles N-speed
E-voltage Two Circuits
Lines 1, 2 and 3
Connect 4 to 5 to 6

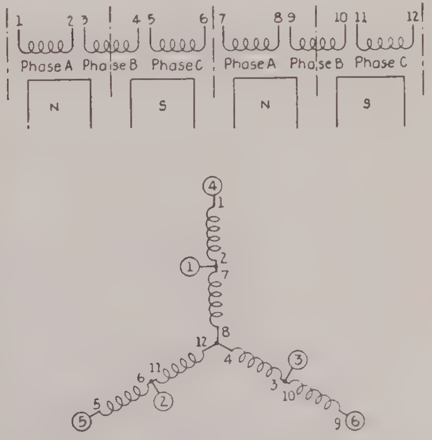


Fig. 12. Three-phase Stator Winding—
120-deg. Phase Belt
2P-poles N/2-speed
E-voltage One Circuit
Lines 4, 5 and 6

Fig. 14 shows the rotor completely assembled. The poles are equally spaced so that the maximum amount of interpolar space can be utilized for the field coils. This motor is used on a 24,000-kv-a. frequency-converter set where it was desirable to place the motor coupling between the rotor and the bearing. In order to reduce the axial length of the set to a minimum, all four collector rings were placed at one end of the rotor. The usual practice is to place the coupling beyond the bearing and then it is desirable to place two collector rings on each side of the rotor.

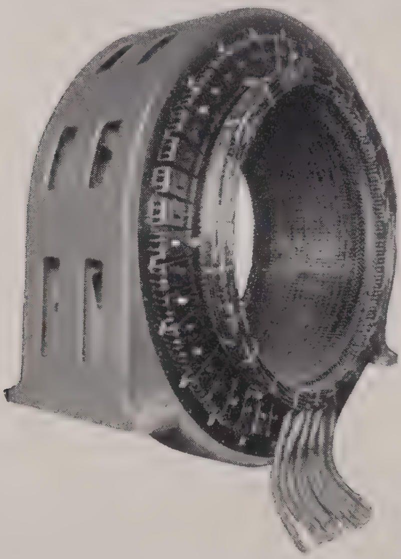


Fig. 13. Stator of a 12/24-pole, 5000/2500-h.p., 600/300-r.p.m., Two-speed Synchronous Motor

Fig. 15 gives a sectional view of the motor showing the unsymmetrical pole tip. The poles are equipped with an amortisseur starting winding, consisting of five bars per pole. Starting tests show that the unsymmetrical pole face has no tendency to cause the motor to lock at a sub-synchronous speed when it is connected for either speed.

An interesting feature in the rotor construction of this two-speed motor is the possibility of arranging the field coils at the high-speed connection to form a two-phase winding

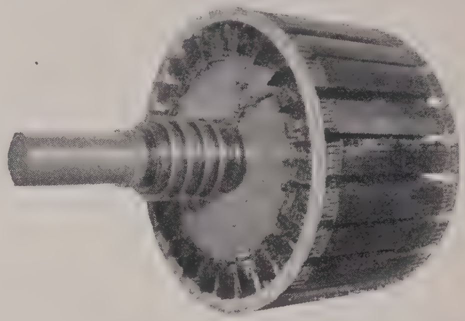


Fig. 14. Rotor of a 12/24-pole, 5000/2500-h.p., 600/300-r.p.m., Two-speed Synchronous Motor

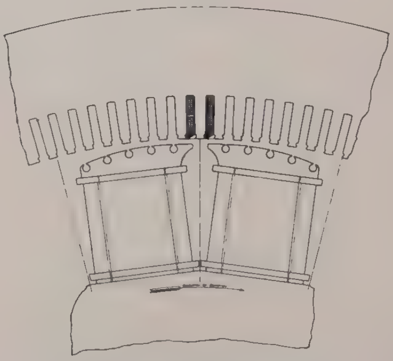


Fig. 15. Sectional View of Two-speed Synchronous Motor

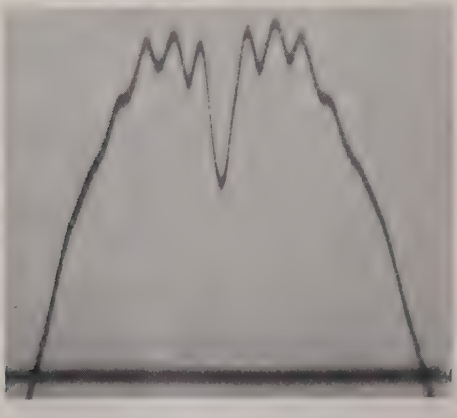


Fig. 16. Flux Wave in Air Gap at High Speed No Load

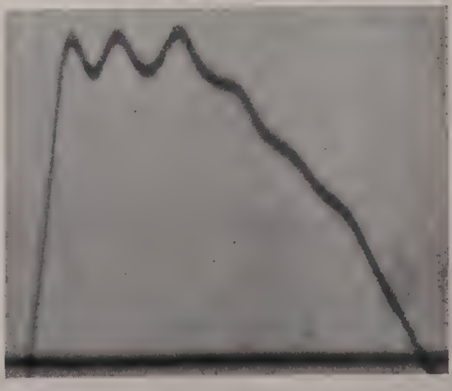
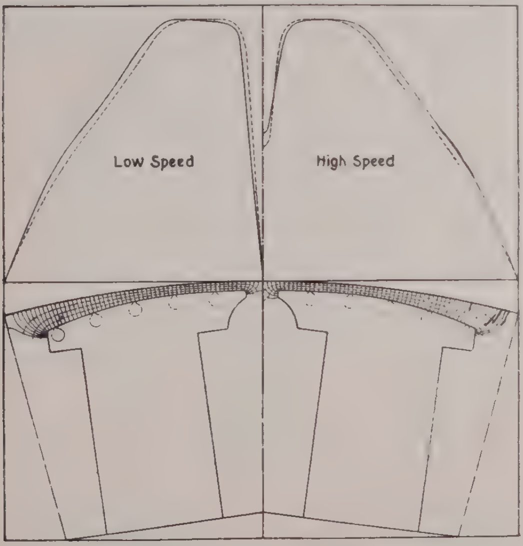


Fig. 17. Flux Wave in Air Gap at Low Speed No Load

which would give considerable starting torque when the motor is operated as an induction motor. This can be done by dividing the coils into two independent groups, each group consisting of alternate coils connected in series, and by short-circuiting the groups separately. The disadvantage of this scheme is that eight collector rings would be required and thus the axial length of the motor would be materially increased.

Predetermination of Motor Characteristics

The actual flux distribution in the air gap is obtained by taking an oscillogram of the voltage induced in an exploring coil placed on the armature face. Figs. 16 and 17 show the flux waves obtained by tests for the high- and low-speed conditions respectively.



One Half Cycle One Quarter Cycle

Fig. 18. Flux Distribution in Air Gap at No Load.
——————Test
……………………Calculated

Fig. 18 shows the outline of the magnetic field structure drawn to scale. The flux distribution in the air gap is obtained graphically by plotting the equipotential lines of magnetomotive force and the tubes of magnetic flux. The influence of the stator and rotor slots is neglected. The dotted lines in Fig. 18 give the calculated flux distribution in the air gap and the full lines show the flux distribution obtained by test. In plotting the actual flux waves (Figs. 16 and 17) in Fig. 18 the ripples due to the rotor amortisseur winding slots were neglected. It should be noted that in Fig. 18 the full wave (one-half cycle) of the low-speed flux wave is shown and only half (one-quarter cycle) of the high-speed flux wave is shown, since this is a symmetrical wave (Fig. 16). The calculated flux waves agree very closely with those obtained by test. Since the predetermination of the flux distribution in the air gap is the foundation upon which the design calculations are based, it follows that the characteristics of a two-speed synchronous motor can be readily predetermined.

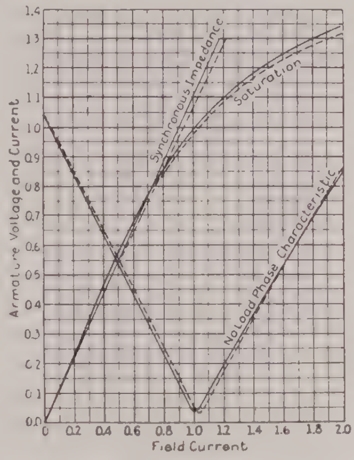


Fig. 19. Characteristic Curves, 12/24-pole, 5000/2500-h.p., 600/300-r.p.m., Two-speed Synchronous Motor at 600-r.p.m , Normal Voltage
——————Test
……………………Calculated

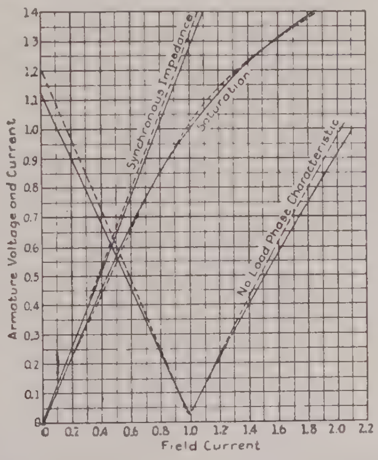


Fig. 20. Characteristic Curves, 12/24-pole, 5000/2500-h.p., 600/300-r.p.m., Two-speed Synchronous Motor at 300-r.p.m., Normal Voltage
——————Test
……………………Calculated

Fig. 19 shows the calculated and test saturation, synchronous impedance, and no-load phase characteristic curves for the high-speed condition; Fig. 20 gives similar low-speed characteristics. Figs. 21 and 22 give the starting torque and starting current for the high- and low-speed conditions respectively. A comparison of Figs. 21 and 22 will show that the starting torque developed with the high-speed connection is much higher than that developed under the low-speed condition. The flux density in the air gap is higher and the reactance is lower for the higher-speed condition, and since the starting torque varies approximately as the square of the flux density and inversely as the reactance, it follows that the high-speed condition should give a higher starting torque.

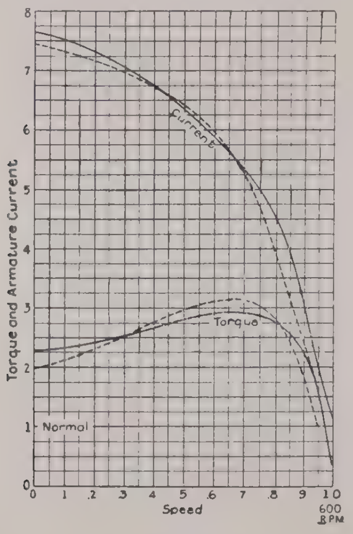


Fig. 21. Starting Torque, 12/24-pole, 5000/2500-h.p., 600/300-r.p.m., Two-speed Synchronous Motor, Normal Voltage, 600-r.p.m. Connection

——— ————Test

....Calculated

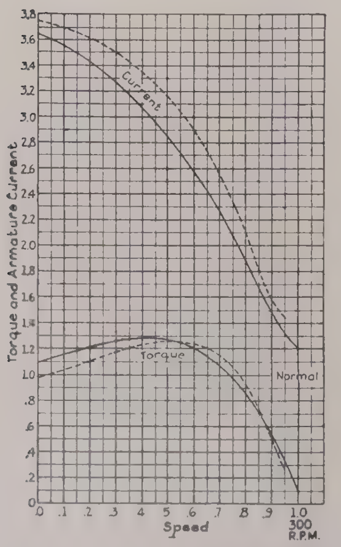


Fig. 22. Starting Torque, 12/24-pole, 5000/2500-h.p., 600/300-r.p.m., Two-speed Synchronous Motor, Normal Voltage, 300-r.p.m. Connection

————————Test

.... Calculated

The efficiency curves of this motor at the high and low speeds are shown in Fig 23. These efficiencies were obtained experimentally by the segregated-loss method and they include the windage and friction loss, open-circuit core loss, short-circuit core loss, armature and field $I^2 R$ losses. These efficiency curves show that at normal load the efficiency is about the same at both speeds. This refers to 5000 h.p., 600 r.p.m., and to 2500 h.p., 300 r.p.m. The stator $I^2 R$ losses are about the same in either case, but the windage and core losses are much less at the low speed. This accounts for the high efficiency at the low speed.

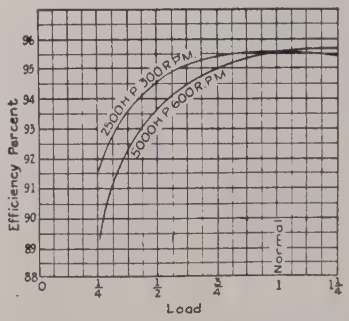


Fig. 23. Efficiency, 12/24-pole, 5000/2500-h.p., 600/300-r.p.m., Two-speed Synchronous Motor

Two-frequency Generator

A two-speed synchronous motor can also function as a two-frequency alternating-current generator when driven at constant speed. Although the flux wave at either frequency deviates appreciably from a sine wave, the voltage wave can be made nearly sinusoidal by a suitable choice of the number of slots and of fractional pitch of the armature coils. Fig. 24 shows an oscillogram of the no-load voltage wave when the above described machine is connected for the normal number of poles, and Fig. 25 for twice the normal number of poles. These voltage waves are really good waves when we consider that the machine was connected two-phase and had an integral number of armature coils per pole per phase. The voltage waves would be much better in a three-phase machine with a fractional number of stator coils per pole per phase. By comparing the flux wave, Fig. 16, with its voltage wave, Fig. 24, and similarly, Fig. 17 with Fig. 25, it will be seen how much the pitch and distribution of the armature coils reduce the various flux ripples and harmonics.

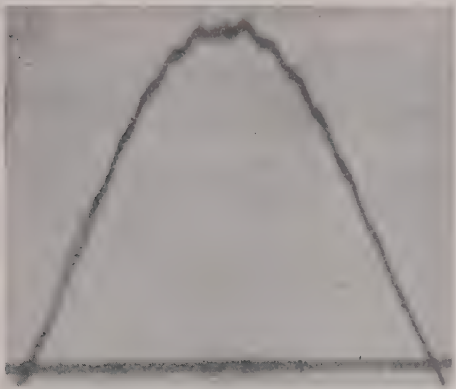


Fig. 24. Voltage Wave at High Speed No Load

The efficiency of this machine obtained by test, when used as a multi-frequency generator, is as follows:

300 Rev. Per Min.

12 poles 30 cycles	24 poles 60 cycles
2000 kw., 1.0 p-f.	2000 kw., 1.0 p-f.
Efficiency 95.4 per cent	95.6 per cent

600 Rev. Per Min.

12 poles 60 cycles	24 poles 120 cycles
4000 kw., 1.0 p-f.	4000 kw., 1.0 p-f.
Efficiency 95.7 per cent	95.8 per cent

The efficiency at 300 r.p.m., 60 cycles is slightly higher than at 300 r.p.m., 30 cycles because the field $I^2 R$ loss is less for the 24-pole connection.

Conclusion

There is nothing special or complicated about the construction of the two-speed synchronous motor. Its performance can be predetermined with the same degree of accuracy as that of the ordinary synchronous motor. It does not require any more attention than an ordinary synchronous machine, and its maintenance expense is just the same. The cost of such a motor is only slightly higher than that of an ordinary synchronous motor whose horse power and speed are equal to the low-speed rating of the two-speed motor. Therefore, this new synchronous motor is a practical machine and should open a new field for synchronous motor application.

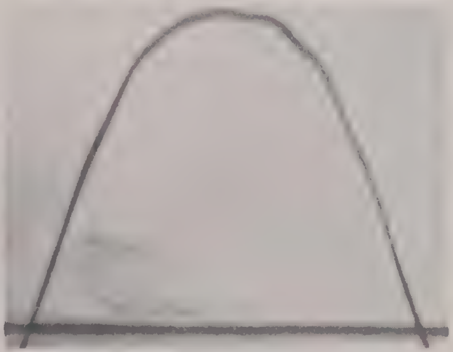


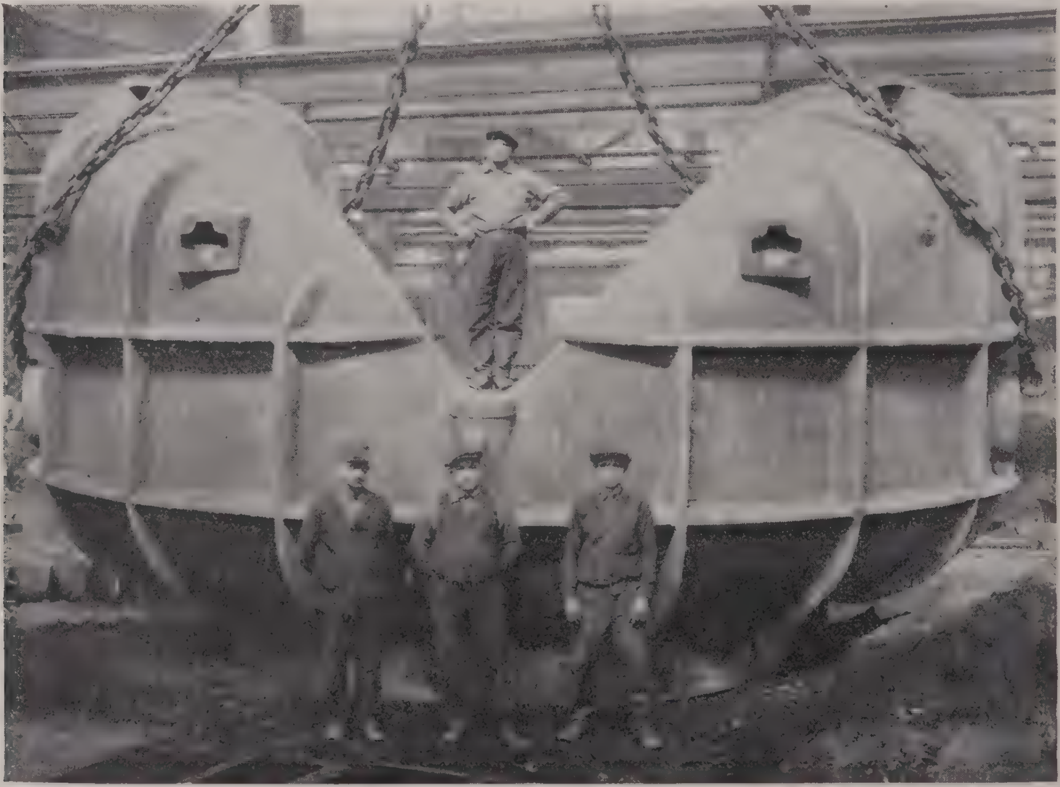
Fig. 25. Voltage Wave at Low Speed No Load

A 60,000-kw. Turbine Casting

In a foundry where large castings of fifteen, twenty, and twenty-five tons in weight are common production, it takes an unusually large casting to excite comment. The General Electric Gray Iron Foundry at Erie recently turned out a turbine casting which is the largest of its type ever produced. It is the upper half of an exhaust hood for a 60,000-kw. steam turbine that is being manufactured by the General Electric Schenectady Works for the New York Edison Illuminating Company.

The photograph shows the casting standing on end on the floor of the foundry after the risers had been removed. The four men in the picture give an idea of its enormous size. The average thickness of the metal of the entire shell is 2½ in. The ribs shown in the picture are 4½ in. thick. The smoothness of these ribs, without any irregularities, gives evidence of the excellent job of molding and casting. The casting weighed 88,900 pounds, nearly 45 tons. It is 24 ft. 6 in. long by 13 ft. 11 in. wide and 11 ft. high. The entire mass of metal as it came out of the moulding sand with cores and arbors weighed nearly 140 tons.

One of the chief difficulties encountered with the casting arose in routing it for shipment from Erie to Schenectady. In order to obtain a route with sufficient clearance under bridges and through stations, it was necessary to avoid Buffalo by using the Buffalo Belt Line. The casting in position on the flat car was too large to go through the city.



An 89,000-lb. Exhaust Hood Casting for a Large Turbine-generating Unit, as it appeared in the foundry of the General Electric Company at Erie, Pa.

A mould for a casting of the same size is now being made at the Erie foundry. The core arbors alone for this casting weighed over 60 tons.

The workmanship required for a casting of this type must be of the highest grade and the casting evidently shows such skill inasmuch as it was one of the finest specimens of foundry quality that was ever sent out from the Erie Works.

The Ballast Resistor in Practice

By H. A. Jones

Research Laboratory, General Electric Company

There are many types of electrical functions conducted within sealed glass bulbs. The most common is the production of light from an incandescent filament; some others are the rectifying action or the relaying action which takes place in the kenotron, radiotron, and similar types of tubes. Still another is the constant-current ballast action exhibited by the tube described in this article. Its peculiar operating characteristics are outlined, the influence of its component parts are explained, and its usefulness in practice is mentioned. In a later issue the "Theory and Design of Ballast Resistors" will be published.—Editor.

A type of resistance used extensively in industrial circuits to maintain a constant current over long periods is called a "ballast resistor," or is more commonly known as a "Nernst Ballast." Two such ballasts are shown in Fig. 1.

Such a resistor is constructed by suspending a pure iron wire in hydrogen gas. The name "ballast" is derived from the peculiar characteristic displayed by this combination; i.e., constant current over a wide range of voltage. Fig. 2 shows the current-voltage characteristic curve of tube *A*, Fig. 1.

Let us assume for example that it is desired to charge a storage battery for a certain number of hours at a constant current. In Fig. 3, *B* represents the storage battery to be charged by current from generator *G*. By inserting at *R* a ballast resistor, of proper design for the desired characteristics, any variation in line voltage will be dissipated by *R* so that *B* may be charged by *G* at a constant current with a variable applied voltage.

Fig. 6 shows type *A* (Fig. 1) ballasts in use on the control panel of a constant-voltage car-axle lighting system.(1)

From the diagrams of connections for this control panel, which are shown in Fig. 4, it will be observed that the type *A* (Fig. 1) ballasts have a double function in this case. The two banks of four ballasts each are used to maintain a constant voltage at the terminals of a variable-speed generator by maintaining a constant current in the field winding. The remaining single ballast is used to maintain a constant current, and hence a constant magnetomotive-force, in the "pull-in" coil of a solenoid type of automatic switch.

Fig. 5 is a laboratory set-up utilizing type *B* (Fig. 1) ballast as a constant-current regulator.

The employment of an iron wire in hydrogen gas to obtain the peculiar ballast characteristic shown in Fig. 2 was first pointed out by Potter.(2)

The first ballasts were used in series with the Nernst glower filaments(3) to maintain a constant current through the glower. It had been shown that the Nernst glowers have a negative temperature coefficient of resistance so that the initial resistance of such a filament is much greater than its resistance under operating conditions. For this reason a ballast resistance, having the property of maintaining a constant current in a circuit in which the resistance has decreased, found valuable application.(4)

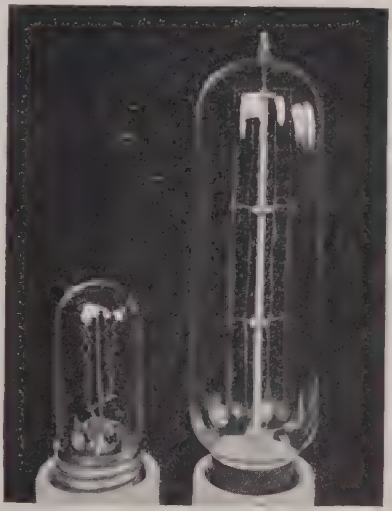


Fig. 1. Crinkled and Coiled Filament Types of Ballast Resistor

A number of years ago Dr. Irving Langmuir worked out the theory of ballast action. Since the results of this investigation on the characteristic properties of various wires in different gases are unpublished, they will be included in this article.

More recently Busch,(5) as a result of a very thorough and complete investigation on the phenomena of wires heated electrically in gases at low pressures, has deduced a theory of ballast-tube action which is in complete accord with that previously deduced by Langmuir.

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(1) This equipment is built by the Electric Storage Battery Company, Philadelphia.

(2) Potter: U. S. Patent No. 743,028; filed Aug. 9, 1899.

(3) Nernst: U. S. Patent No. 685,724; filed April 28, 1898.

(4) For example, see A. J. Wurts, *Trans. A.I.E.E.*, Vol. 18 (1901).

(5) H. Busch, *Ann. der Phys. 64*, 401 (1921).

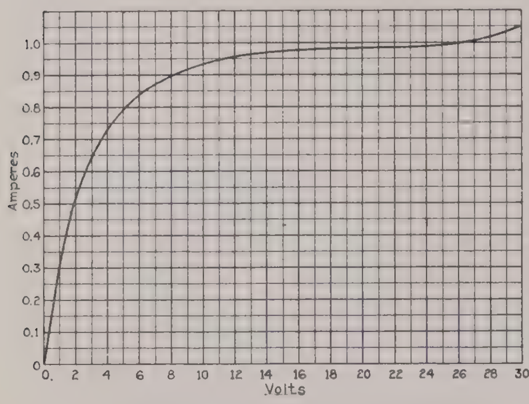

Fig. 2. Volt-ampere Characteristic Curve of type *A* (Fig. 1) Ballast Resistor

However, Busch's method of presentation is rather involved and in view of the simpler conceptions introduced by Langmuir into the entire subject of heat conduction and convection in gases, it seems worth while to present a detailed discussion of the fundamental principles of ballast action and the design of ballast resistances.

A theoretical characteristic curve may be constructed for any iron wire if the wire is assumed to be at a uniform temperature over its entire length so that the influence of end corrections does not enter into consideration.

The relation between potential (E), current (I), resistance (R), and watts (W) is well known from the formulas:

$$RI^2 = W, \text{ or } I = \sqrt{\frac{W}{R}} \qquad (1)$$

$$E = RI, \text{ or } E = \sqrt{W\,R} \qquad (2)$$

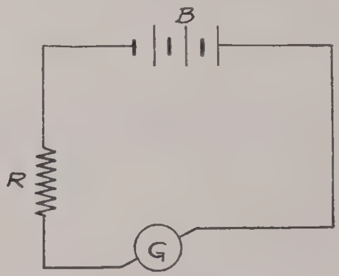

Fig. 3. Elementary Diagram Illustrating the Use of a Ballast Resistor in Battery-charging Operations

Since both W and R are functions of temperature, a volt-ampere characteristic curve may be plotted for any diameter of iron wire when the *total* heat loss W expressed in watts and the ohmic resistance of the filament R at the operating temperature are known.

The results of calculations for an iron wire, based on the foregoing formulas, are shown in Curves I, II, and III, Fig. 7, where $\sqrt{\frac{W}{R}}$ has been plotted against $\sqrt{W\,R}$. The ambient temperature was assumed to be 100, 300, and 600 deg. for Curves I, II, and III respectively.

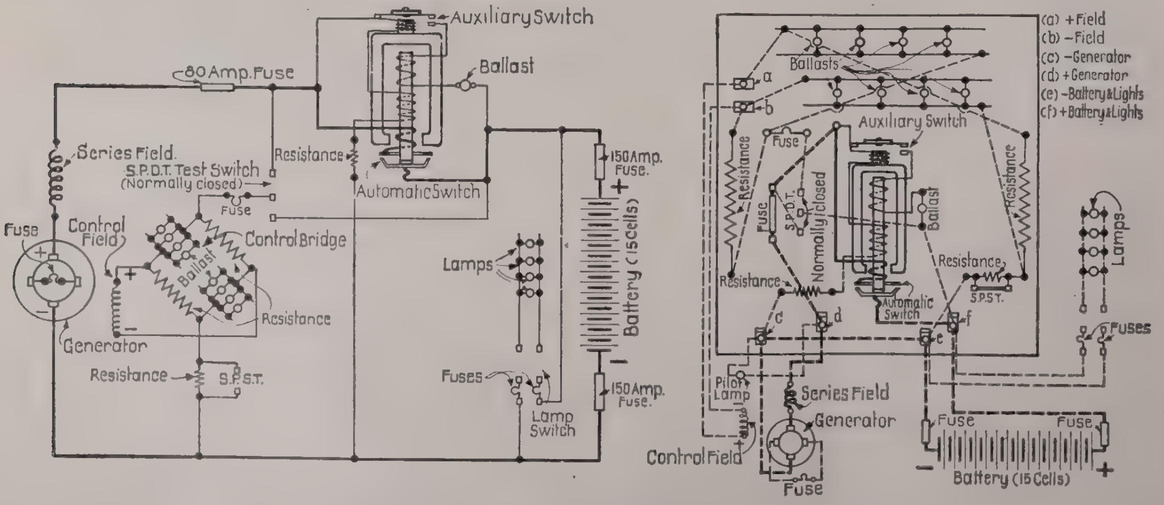

Fig. 4. Diagrams of the Connections of the Control Panel Shown in Fig. 6

(Courtesy of Electric Storage Battery Co.)

In the portion of Curves I and II, Fig. 7, which shows a negative slope, dT/dI or dE/dI has a negative value. To evaluate dT/dI or dE/dI, equations (1) and (2) may be written logarithmically:

$$2 \log I = \log W - \log R \tag{1a}$$

$$2 \log E = \log W + \log R \tag{2a}$$

Differentiating these equations:

$$2(d \log I) = d \log W - d \log R \tag{1b}$$

$$2(d \log E) = d \log W + d \log R \tag{2b}$$

Now since W, the total heat loss in watts from a filament operating in a gas, and R, the resistance of the filament at the operating temperature, are both functions of the temperature over any small interval of temperature their values may be written:

$$W = AT^{n_W} \tag{3}$$

and

$$R = BT^{n_R} \tag{4}$$

Here n_W and n_R are exponents of the absolute temperature with which W and R increase with the absolute temperature.

Equations (3) and (4) may be written

$$n_W = \frac{d \log W}{d \log T} = \frac{T}{W} \frac{dW}{dT} \tag{3a}$$

and

$$n_R = \frac{d \log R}{d \log T} = \frac{T}{R} \frac{dR}{dT} \tag{4a}$$

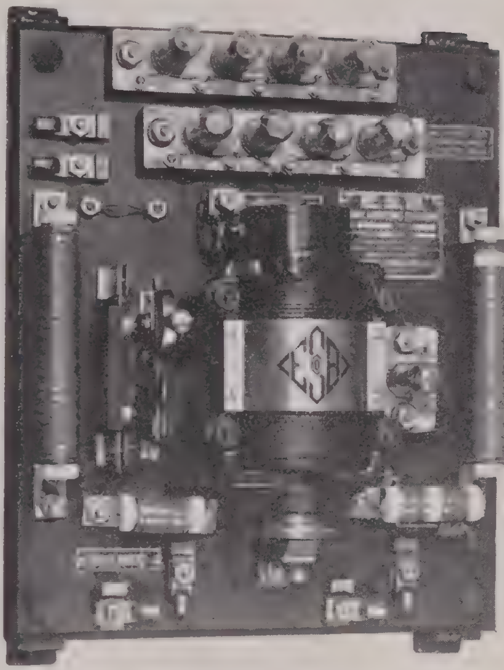

Fig. 6. Ballast Resistors of type *A* (Fig. 1) on the Control Panel of a Constant-voltage Car-lighting System. (*Courtesy of Electric Storage Battery Co.*)

If n_W and n_R are substituted for $\frac{d \log W}{d \log T}$ and $\frac{d \log R}{d \log T}$ in equation (1b), there is obtained:

$$\frac{I}{T} \frac{dT}{dI} = \frac{2}{n_W - n_R} \tag{5}$$

from which $\frac{dT}{dI}$ may be evaluated.

Similarly, it may be shown by dividing equations (1b) and (2b) and substituting n_W and n_R for $\frac{d \log W}{d \log T}$ and $\frac{d \log R}{d \log T}$ respectively, that

$$E'_{(I)} = \frac{dE}{dI} \cdot \frac{I}{E} = \frac{n_W + n_R}{n_W - n_R} \tag{6}$$

It follows further from equations (1b) and (2b) that

$$R'_{(I)} = \frac{dR}{dI} \frac{I}{R} = \frac{2\, n_R}{n_W - n_R} \tag{7}$$

The logarithmic differential quotients n_W and n_R of the functions W_T and R_T are

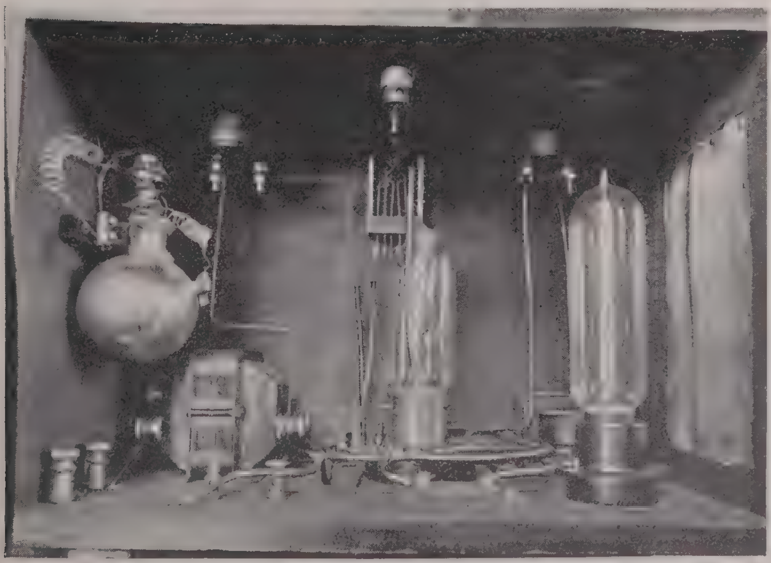

Fig. 5. Ballast Resistor of type *B* (Fig. 1) in a Laboratory Set-up

the exponents with which W and R increase with the absolute temperature.

It follows further, since $\frac{dT}{dI}$ or $\frac{dE}{dI}$ must be less than zero in order to obtain the theoretical negative characteristic in Curves I and II, Fig. 7, that

$$n_W - n_R < 0, \qquad (8)$$

i.e., the heat loss W must increase proportionately slower with the absolute temperature than the resistance R.

The plot showing the relation between the resistance of iron, nickel, and tungsten in terms of resistance at 0 deg. C. and the absolute temperature is given in Fig. 8. From these data, taken from A. A. Somerville's[(6)] measurements on the temperature coefficient of resistance, the n_R curves have been derived and are shown in Fig. 9.

For platinum, silver, copper, and tungsten, n_R is nearly independent of temperature, i.e., for these metals the increase in resistance is nearly linear with the increase in the absolute temperature. For iron and nickel, however, n_R attains very high values. The n_R curve for iron shows a slight maximum at 300 to 400 deg. C. and a sharp maximum at 700 deg. C. The n_R curve for nickel shows a sharp maximum at about 200 deg. C. The maximum values of n_R for both metals are greater than 2.

The values of $n_W = \frac{T}{W}\frac{dW}{dT}$ as functions of temperature for hydrogen and air are shown in Fig. 9. The method adopted to evaluate the total heat loss in watts W per unit length of filament will be analyzed in detail in an article, "Theory and Design of Ballast Resistors," to be published in this magazine.

If n_W and n_R are plotted as functions of temperature, it is obvious that the n_W curve lies below the n_R curve in the temperature range in which equation (8) is satisfied. At intersections where $n_W - n_R = 0$, equation (6) gives $\frac{dE}{dI} = \propto$, which corresponds to a current maximum or minimum in Curves I and II, Fig. 7. Hence, from the plots of n_W and n_R in Fig. 9, there is obtained the temperature range in which a negative characteristic may be expected to occur. The n_W curve for hydrogen at 760 mm. lies below the n_R curve for iron between 885 deg. K. and 1035 deg. K. Hence in this range of filament temperatures, equation (8) is satisfied and a negative characteristic may be expected for iron wire in hydrogen at this pressure.

Consider now the problem of the theoretical volt-ampere characteristic curve, as relating to a negative characteristic for an iron wire in hydrogen. (See Curves I and II, Fig. 7.) This theoretical negative characteristic curve has never been observed in practice. It is possible to demonstrate the reason for this analytically.[(5)] If two similar resistances with negative characteristics are arranged in series with a constant source of potential, E_o, there exists the relation:

$$E_o - e_1(i) = e_2(i)$$

where $e_1(i)$ and $e_2(i)$ are the divisions of voltage over the two resistances respectively. The possible similar points on the characteristic curves in the two cases are obtained by

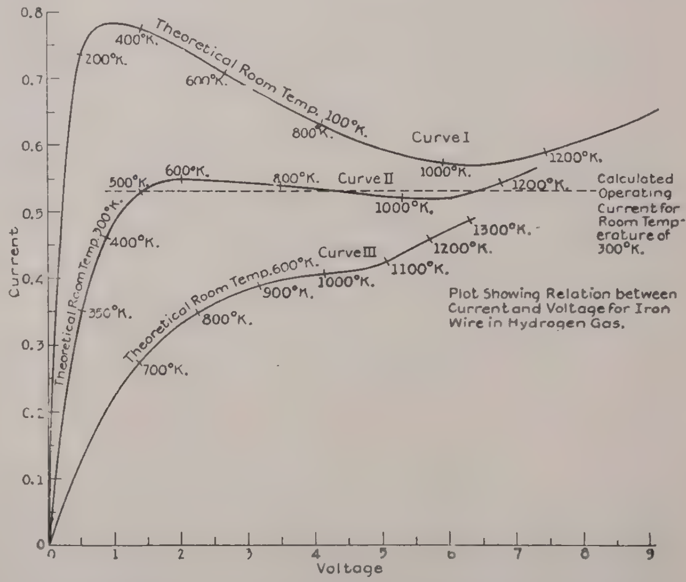

Fig. 7. For the three Curves marked "theoretical," the square root of the quotient of the watts lost per cm. length in hydrogen at atmospheric pressure divided by the ratio of the resistivity of iron at the filament temperature to that at 0 deg. C. $\left(\sqrt{\frac{W}{\frac{R_T}{R_o}}}\right)$ has been plotted against the square root of their product $\left(\sqrt{\frac{WR_T}{R_o}}\right)$

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(6) A. A. Somerville: *Phys. Rev.* 31, 261 (1910).

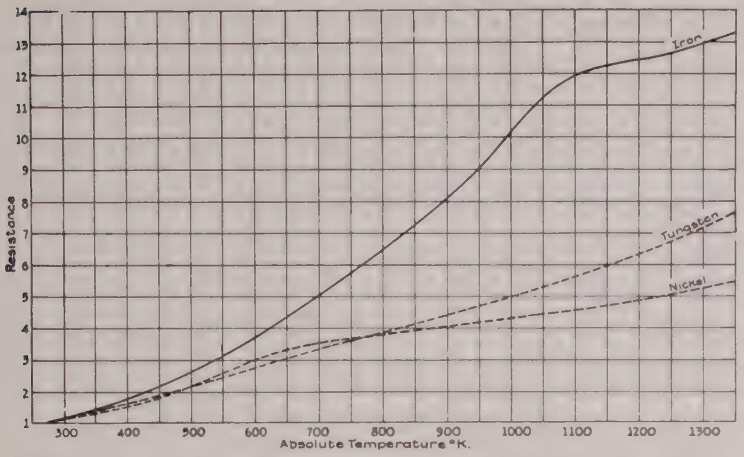

Fig. 8. Relation Between the Resistance of Iron, Nickel, and Tungsten in Terms of the Resistance at 0 deg. C. and the Absolute Temperature

plotting $e_2(i)$ and $E_o - e_1(i)$. These curves intersect at three points as shown in Fig. 10.

Now since S_1 and S_3 are on the ascending curves in each case they represent stable conditions. The intersection at the middle point S_2 represents a point of similar condition in both wires, i.e., a condition in which they are at the same temperature and the same voltage drop per unit of length.

It may be shown that for the point S_2 to be stable, $n_{W'} - n_R$ must be greater than zero. But since according to equation (8) $n_{W'} - n_R$ must be less than zero for a negative characteristic, the point S_2 corresponds to an unstable condition. Therefore, for two similar resistances with negative characteristics connected in series, the condition that both resistances shall be at the same temperature is impossible.

Applying these considerations to any number of negative resistances connected in series, it may be shown in a similar manner that there must be an uneven temperature distribution along them.

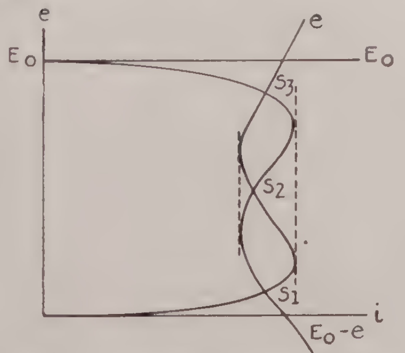

Fig. 10. Volt-ampere Characteristic Curves for Two Similar Ballast Resistors Connected in Series

The experimentally observed characteristics for an iron wire in various pressures of hydrogen are shown in Fig. 11. The current increases in a normal manner with increasing voltage to a certain value and then remains practically constant for a considerably extended range of voltage. This region of the flat characteristic is called the "ballasting range." When the value of the current corresponding to this range is reached, a slight increase in the voltage impressed on the wire causes a sudden corresponding increase in current which then slowly decreases with time to the original ballasting value. For wires of large diameter, as much as 10 minutes may elapse before the current reaches its constant value in the ballasting

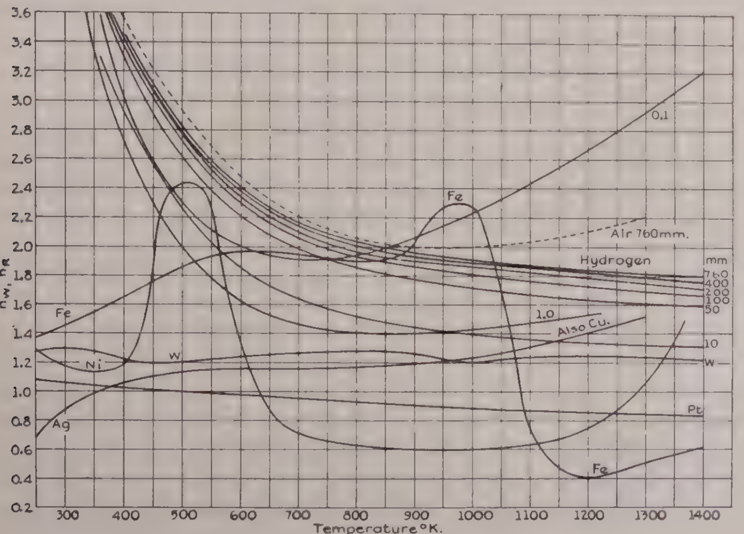

Fig. 9. Plot of $n_{W'}$ for Hydrogen (at Various Pressures) and Air (at Atmospheric Pressure) and of n_R for Iron, Nickel, Tungsten, Copper, Silver, and Platinum Against Temperature

range. Above this flat region, the current attains a constantly higher value with each new increment of voltage, though the curve does not rise as sharply as before the ballast range is reached.

When the ballasting value of the current is first attained, it is observed that the filament shows a small visible hot spot while the remainder of the wire is at a much lower temperature. As the voltage is slowly increased, this visible red spot gradually spreads toward both leads until, as the upper limit of ballasting voltage is reached, the entire filament appears at a visible bright red heat (about 760 deg. C.) throughout its length. As the voltage is increased beyond this point, the temperature of the entire filament increases uniformly and the current no longer remains constant.

In one experiment, a filament which was tapered at one end developed the original hot spot at this point. With increased energy input, the hot spot then spread continuously until it reached the other lead.

For comparison with the theory, the calculated characteristic curve for this same wire in 9 mm. pressure of hydrogen is also drawn in Fig. 11. When due account is taken of the pressure differences, the agreement is found to be good.

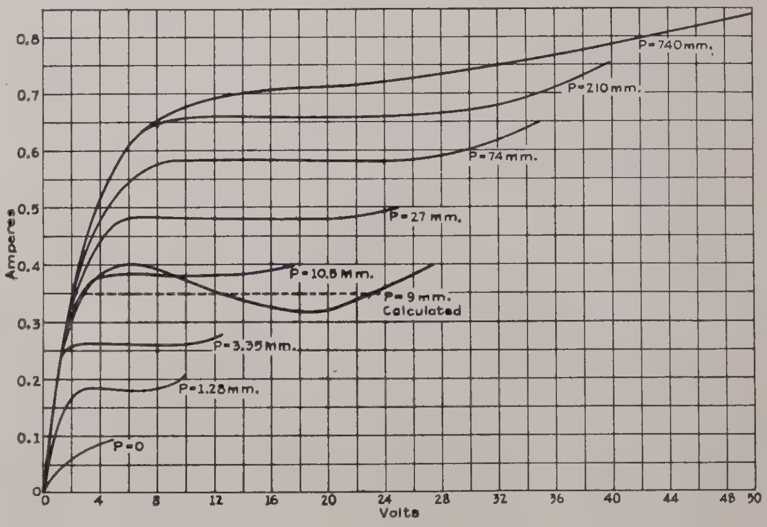

Fig. 11. Experimentally Observed Volt-ampere Characteristic Curves for an Iron Wire in Hydrogen at Various Pressures

Effect of Water Vapor and Overloading

In connection with an investigation which the writer carried out on the maintenance of the rating of ballast resistors during their life, certain phenomena were observed which it is of interest to mention.

A microscopic examination of iron wires which had been run repeatedly above the "ballasting range" (i.e., above the normal rating) showed that large crystals had developed not only linearly (in the direction of the wire) but also at an angle to the wire surface, so that the wire showed distortion with a consequent increase in cross-section at certain points, and a consequent decrease in cross-section immediately adjacent to these points. While there is some difference of opinion among metallographers regarding the α to β iron transition point at 768 deg. C., Burgess and Kellberg⁽⁷⁾ report a slight increase in the specific volume of iron at this temperature. Authors are unanimous, however, on the matter of the β to γ iron transition at 898 to 908 deg. C., where a sudden contraction in volume occurs. This may be readily observed when a wire is run slightly above 900 deg. C., or well above the normal limit of the flat ballasting characteristic, when a sudden twitching and shrinking occurs. The wire begins to offset and distort at this temperature. Experiments have shown that the maximum offsetting and consequent decrease in length is caused more readily by repeatedly passing through this β to γ range of temperature than by simply maintaining the temperature above 900 deg. C. for the same period of time. Continued use of the wire in the β to γ iron region of temperature results finally in sufficient decrease in the total length of the wire to cause fracture.

To obviate this difficulty as far as possible, the iron wire filaments are usually crinkled to approximately two-thirds of their original length before mounting in the bulb.

This same result of passing through the β to γ iron region of temperature may also occur through a change in the heat conductivity of the gas. Any oxides present in the metal parts of the device, either in the iron filament or in the metal lead-in and support wires, will be easily reduced by the heated

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(7) Burgess and Kellberg, *Bur. of Std. Bulletin*, 457 (1915), furnish a very complete bibliography of the literature on this controversial point.

hydrogen gas when the resistor is in operation. The end product of the interaction of any oxides present with the hydrogen is water vapor at the same pressure, and, since calculation shows that under similar conditions of pressure and temperature water vapor is only 20 per cent as efficient a heat conductor as hydrogen, the effect is to decrease greatly the energy dissipated by the filament in the ballast range of temperatures, i.e., for the limiting voltages in the ballast range, the characteristic current is lower when water vapor replaces hydrogen.

The effect of dissipating the rated amount of energy in a ballast containing water vapor in the hydrogen is to increase the filament temperature above the ballast range and, finally, when a sufficient amount of water vapor is present, the wire passes through the β to γ iron region of temperatures where distortion and shrinkage occurs and a fracture of the filament results.

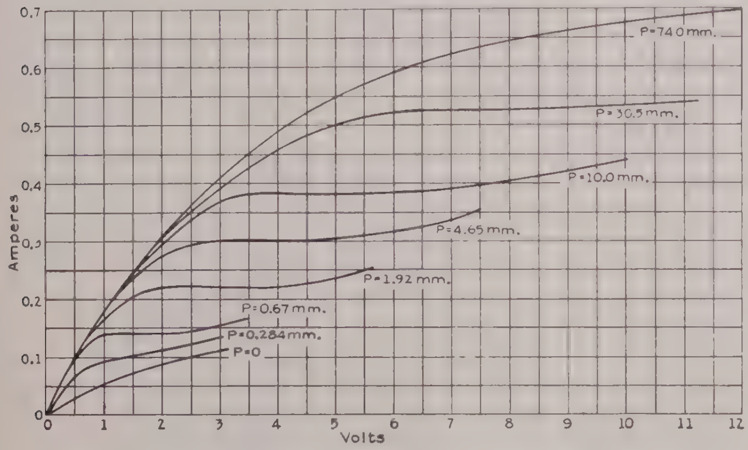

Fig. 12. Experimentally Observed Volt-ampere Characteristic Curves for a Nickel Wire in Hydrogen at Various Pressures

An actual case that developed in practice showed the following result: The iron filament whose total weight was 8.6×10^{-3} gm. was 8.9×10^{-3} cm. in diameter and 17.6 cm. long. The nickel supports had a total weight of 0.27 gm. The volume of the bulb was 22 cm.^{3} Assuming a pressure of hydrogen of 20 cm. Hg, calculation shows that 1 mm. pressure of hydrogen would be converted to 1 mm. of water vapor if 3.25 per cent of iron oxide (assumed to be Fe_3O_4) were present in the iron wire. Similarly 1 mm. pressure of water vapor would be formed during the operation of this tube from 0.034 per cent of nickelic oxide (NiO) in the nickel parts.

Experiments with this type of ballast resistor showed that the conversion of 0.5 per cent of the hydrogen to water vapor when 20 cm. of hydrogen were initially present decreases by 1 per cent the energy input necessary to maintain the limiting ballast temperatures; also the length of the ballasting range in volts per cm. length of filament is decreased by 1 per cent when 0.5 per cent of water vapor is present in the hydrogen. The decrease in the energy dissipated and the decrease in the voltage range for ballast action were found to be approximately linear with an increase in water vapor content up to 8 per cent.

Since iron interacts chemically with water vapor to give iron oxide and hydrogen, no water vapor should be permitted to be present for this reason as well as for the previously stated fact that it is only 20 per cent as efficient a heat conductor as the same pressure of hydrogen. The $n_{W'}$ curve for air has been drawn in Fig. 9 for comparison. Its use is also precluded due to chemical interaction with the iron wire.

The $n_{W'}$ and n_R curves for hydrogen and nickel lead to the expectation of a ballasting characteristic for this case. That this is borne out by experiment may be observed in Fig. 12 which shows the experimentally observed characteristics for a nickel wire in hydrogen gas at various pressures. It is noteworthy that ballasting does not occur in the case of nickel wire and hydrogen at 740 mm. pressure. From the plot of n_W and n_R for hydrogen and nickel in Fig. 9, it may be observed that $n_{W'} - n_R$ is always greater than zero for this case.

In conclusion, the writer acknowledges the assistance of Mr. H. Huthsteiner in performing the experimental work mentioned here. He is also greatly indebted to Dr. I. Langmuir for the use of the older data, and to Dr. S. Dushman for many helpful suggestions and constructive criticisms.

Windage Losses in Air, Hydrogen, and Carbon Dioxide

By Chester W. Rice

Research Laboratory, General Electric Company

In the early days when man travelled slowly, he gave little heed to the dissipation of effort occasioned by air resistance. But today, confronted by the problems of the airplane and many other high-speed machines of modern civilization, engineers must recognize and take into account the serious power losses due to "windage" and fluid resistance. Mr. Rice's article presents a comparative study of power losses accompanying the motion of bodies in several gases, and makes a practical application of the fact that these losses vary nearly in proportion to the density of the gas.—Editor.

When relative motion exists between a solid and a liquid, energy is dissipated. If the relative velocity is low, we have the familiar case of viscous resistance, but as the velocity is increased we find that at a certain critical speed, depending on the properties of the fluid and dimensions of the solid, eddies burst into existence and cause a change in the law of resistance. The latter condition, which is usually termed "turbulent motion," is the one most frequently met in engineering problems.

Extensive studies have been made upon fluid friction by W. Froude.(1) His tests consisted in towing boards of different dimensions and degrees of roughness through water at various speeds and observing the resistance offered. Osborne Reynolds(2) studied the case of water flowing in tubes, and determined the condition under which the flow changes from the parallel stream line condition to turbulent motion. He followed this remarkable experimental work some years later with a theoretical investigation of the problem.(3) Unwin(4) studied the case of rotating disks in water.

Much theoretical work on the problem of turbulent fluid motion has been done by Kelvin, Rayleigh, and others without, however, having as yet reached a completely satisfactory theory of the phenomenon. For a discussion and summary of this work reference may be made to Lamb's Hydrodynamics.(5) A summary from the engineering point of view may be found in Unwin's Hydraulics.(6)

The small amount of work done on the resistance to moving bodies offered by gases and vapors has been summarized by Stodola.(7) Further work has been summarized more recently by Buckingham.(8)

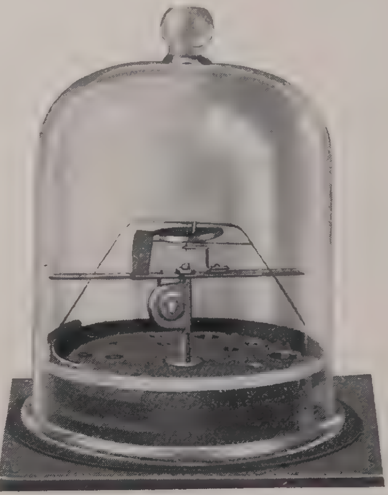

Fig. 1. Revolving Disk Apparatus for the Measurement of Windage Losses in Gases

Several years ago Dr. W. R. Whitney pointed out the desirability of using hydrogen as the cooling medium for large electrical machines. A subsequent investigation showed that the idea of using hydrogen as a cooling medium in electrical machinery was proposed some years earlier by Max Schuler.(9) As a result of this suggestion active work was started by the present writer to determine the windage losses, heat transfer, etc., to be expected when operating electrical machines in different gases, with special reference to the use of hydrogen. The work on heat transfer has already been reported.(10) (11) (12)

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(1) W. Froude, *British Association Reports*, 1875.

(2) Osborne Reynolds, "An Experimental Investigation of the Circumstances which determine whether the motion of water shall be direct or sinuous, and of the Law of Resistance in Parallel Channels," *Phil. Trans. Roy. Soc.*, 1883, Part III, p. 935.

(3) Osborne Reynolds, "On the Dynamical Theory of Incompressible Viscous Fluids and the Determination of the Criterion," *Phil. Trans. Roy. Soc.*, A, Part 1, 1895, p. 123.

(4) W. C. Unwin, *Proc. Inst. Civil Engineers*, LXXX, 1885.

(5) Horace Lamb, "Hydrodynamics," Cambridge University Press, p. 591.

(6) W. C. Unwin, "A Treatise on Hydraulics," Adams and Charles Black, p. 132.

(7) A. Stodola, "The Steam Turbine." Translation by L. C. Loewenstein, D. Van Nostrand Co., p. 129.

(8) "Windage Resistance of Steam Turbine Wheels," *Bureau of Stds.*, Vol. 10, p. 191, 1914; also *Engineering*, March 13, 1914.

(9) Max Schuler, American Patent, No. 1,453,083. Filed Oct. 25, 1916. Issued April 24, 1923.

(10) Chester W. Rice, "Free and Forced Convection of Heat in Gases and Liquids," *Trans. A.I.E.E.*, Vol. XLII, p. 653, 1923.

(11) Chester W. Rice, "Free Convection of Heat in Gases and Liquids, II," *Journal A.I.E.E.*, p. 1141, Dec., 1924.

(12) Chester W. Rice, "Forced Convection of Heat in Gases and Liquids, II," *Jour. Industrial and Engineering Chemistry*, Vol. 16, No. 5, p. 460, 1924.

Fig. 1 will give a general idea of the apparatus used, and Fig. 2 is a cross-section giving the principal dimensions. The notched and perforated disk *A* is rotated at various speeds within the short cylinder *B*. The rotation of *B* is resisted by a flat spiral spring and damping is provided by the oil-filled trough *D*. The rotary deflection of the cylinder *B* is used as a measure of the drag or force which the rotating disk exerts upon it. In these experiments the inner surface of the cylinder *B* was coated with rough sand.

The apparatus is crude as it was only intended to obtain relative values of windage loss for different gases. It is believed that an apparatus of this kind supplied with a guard ring to define accurately the surface acted upon would be found convenient for obtaining accurate data on the friction as expressed by the force per unit area. The use of mercury as a damping liquid would also constitute an improvement.

Fig. 3 summarizes the data obtained for air, hydrogen, and carbon dioxide at atmospheric pressure and room temperature, roughly assumed to be 76 cm. of mercury and 25 deg. C. The rotary deflections of the short cylinder *B*, as measured in centimeters on the surface of the bell jar, are plotted as ordinates. The abscissas represent the peripheral velocities of the disk in meters per second as calculated from the motor revolutions obtained from the speed counter with the help of a stop watch. Curves are also shown of a run in air at a pressure of 5.3 cm. mercury, for comparison with hydrogen, since at this pressure air has approximately the same density as pure hydrogen. The fact that the hydrogen curve lies above the air curve of supposedly corresponding density is due to the presence of impurities in the hydrogen used which was taken from the laboratory pipe lines. The deviation appearing on the graph represents a density ratio, between pure hydrogen and that used, of 3 to 4 which would correspond to an air impurity of approximately 2.5 per cent. An analysis of the hydrogen showed an impurity of this order of magnitude.

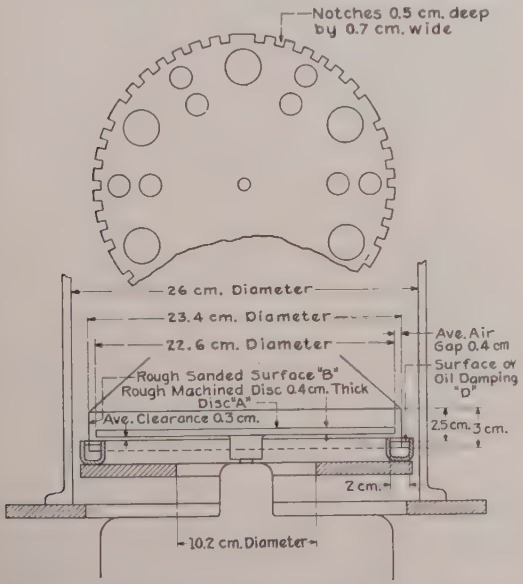

Fig. 2. Windage Apparatus in Cross-section. The disk is revolved by a motor installed below the metal base

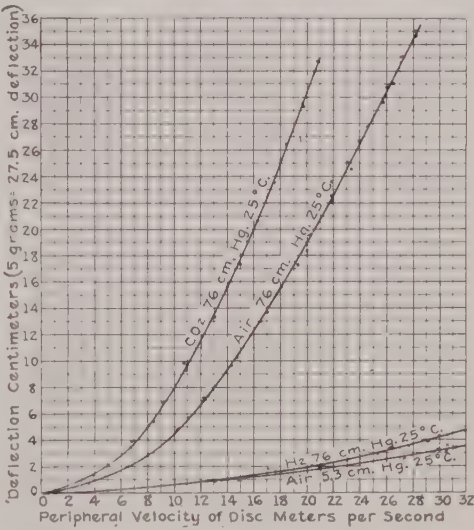

Fig. 3. Variation of Windage Losses with Disk Velocity for Several Gases

Fig. 4 gives the variation of the drag as a function of air pressure for three different values of the peripheral velocity of the disk. These tests were made by gradually exhausting the apparatus while the disk was in rotation. Inspection of the curves shows that the windage loss at constant velocity is approximately proportional to the density of the gas under the conditions of turbulent motion here existing.

In Fig. 5 the curves of Fig. 3 are plotted on a log-log scale from which we see that their common slope is approximately 1.91 for the condition of these experiments, or that the frictional force is approximately proportional to the square of the velocity.

By measuring the displacement between the curves for CO_2, air, and hydrogen it will be observed that here again the windage loss is approximately proportional to the density of the gas.

The foregoing conclusions can be arrived at directly by applying the method of dimensions as was pointed out by Rayleigh.(13) Further examples and references to the application of this powerful tool to physical problems are given by Rayleigh,(14) Tolman,(15) Buckingham,(16) Bridgeman,(17) Lewis and Adams,(18) Davis,(19) and others. Buckingham(20) has recently applied the method to the problem of windage losses of steam turbine wheels.

Before attempting to apply the principle of dimensions it is necessary to determine all of the physical quantities on which the phenomenon under investigation may reasonably be expected to depend. This can usually be done by applying our knowledge of the physics of the problem. In the present case, the resistance or force f will depend upon the size of the apparatus, in other words, on its linear dimensions. In order to describe our apparatus, we may select the diameter d of the rotating disk, or any other convenient linear dimension as our unit, and then describe the other parts of the apparatus as ratios of the diameter. For example, the air gap may be $\frac{1}{10}$ of the diameter, the notches in the edge of the disk may be $\frac{1}{100}$, etc. We can thus completely describe all of the size factors in terms of the diameter d, and a series of numerical ratios (r_1, r_2, etc.). The force can further be reasonably assumed to be a function of the peripheral velocity v together with a series of numerical velocity ratios (r_1', r_2', etc.) to represent the complex eddying stream motion. We would also expect that the viscosity μ of the gas or liquid would enter, certainly at low velocities. The density ρ would naturally be considered because of the kinematic nature of the problem. We may therefore write

$$f=\psi\ (d,\ \mu,\ \rho,\ v,\ r_1,\ r_2\,..\,r_1',\ r_2') \qquad (1)$$

Now in general the method of dimensions will not tell us anything about numerical multipliers, therefore we may as well take all of the numerical ratios out of equation (1) and write it as follows:

$$f=C\ d^x\ \mu^y\ \rho^z\ v^n \qquad (2)$$

where C = numerical constant to be determined by experiment or where possible by calculation.

We now consider the dimensions of the various factors in terms of length L, mass M, and time T as our fundamental units.

Force $f=L\ M\ T^{-2}$
Diameter $d=L$
Viscosity $\mu=L^{-1}\ M\ T^{-1}$
Density $\rho=L^{-3}\ M$
Velocity $v=L\ T^{-1}$

We may then substitute these values in equation (2) and write

$$(L\ M\ T^{--2})^1=C\ (L)^x\ (L^{-1}\ M\ T^{-1})^y\ (L^{-3}\ M)^z\ (L\ T^{-1})^n \qquad (3)$$

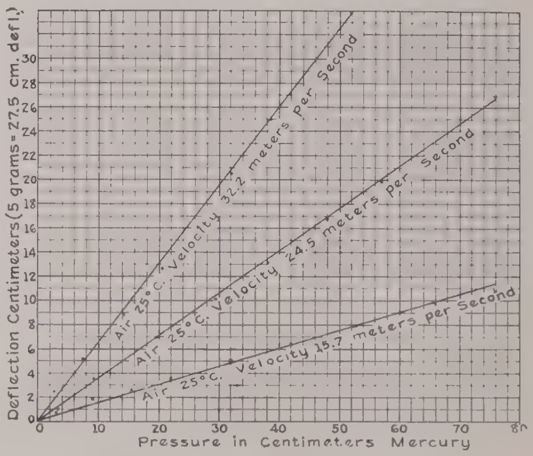

Fig. 4. The Effect of Barometric Pressure Upon Windage Losses in Air

In order that this may represent a true physical equation, the dimensions in L, M, and T must be equal on both sides of the equation. In order to satisfy this condition we can write the following simultaneous equations:

$$\left.\begin{array}{ll} \text{By } L, & 1=x-y-3z+n \\ M, & 1=y+z \\ T, & -2=-y-n \end{array}\right\} \qquad (4)$$

Solving in terms of n we have

$$\left.\begin{array}{l} x=n \\ y=2-n \\ z=n-1 \end{array}\right\} \qquad (5)$$

Therefore,

$$f=C\ d^n\ \mu^{(2-n)}\ \rho^{(n-1)}\ v^n \qquad (6)$$

If we assume that for low velocities $n=1$, that is, the force is proportional to the velocity, then

$$f=C\ d\ \mu\ v \qquad (7)$$

Here d can be taken as any linear dimension we choose by assigning a suitable value to the constant C. If we wish to express this law of viscous resistance in a more familiar form, we may write it

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(13) *Scientific Papers*, Vol. III, p. 575; or *Phil. Mag.* XXXIV, pp. 59–70, 1892.

(14) *Nature*, Vol. 95, 1915, p. 66.

(15) *Phys. Rev.* 3, 244, 1914; 4, 145, 1914; 6, 219, 1915; 8, 8, 1916; 9, 237, 1917.

(16) *Phys. Rev.* 4, 345, 1914.

(17) *Phys. Rev.* 8, 423, 1916; also "Dimensional Analysis," *Yale University Press.*

(18) *Phys. Rev.* 3, 96, 1914.

(19) *Phil. Mag.* 40, 692, 1920.

(20) *Loc. cit.* (8).

$$f = K \frac{A}{l} \mu v \tag{8}$$

where A is the area of the surface in square cm. and l is a linear dimension. If we further let l be the spacing in cm. between two large parallel plates, then K becomes unity and we have the law of viscous resistance between parallel planes:

$$f = \frac{A \mu v}{l} \text{ dynes} \tag{9}$$

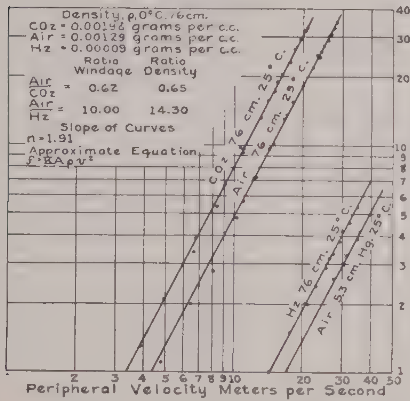

Fig. 5. Log-log Plot of the Windage Losses Shown in Fig. 3

where A = Area of cross-section of the fluid in sq. cm.
μ = Viscosity of the fluid in c.g.s. units
v = Relative velocity of plane surfaces in cm. per sec.
l = Spacing between planes in cm.

Now under the conditions of turbulent motion we may assume $n=2$ in which case equation (6) becomes

$$f = C\, d^2 \rho v^2 \tag{10}$$

Here we may write the area A for d^2 by suitably changing the value of C. Then equation (10) becomes

$$f = K A \rho v^2 \text{ dynes} \tag{11}$$

where K = Numerical constant to be determined by experiment
A = Area of cross-section of the fluid in sq. cm.
ρ = Density of the fluid in grams per c.c.
v = Relative velocity between surfaces in cm. per sec.

It will be observed that under these conditions the force is proportional to the area, density, and velocity squared; and independent of the viscosity, as our experiments indicated. Thus, the windage loss in hydrogen and air at the same density for the case of turbulent motion should be approximately the same even though the viscosity of hydrogen is only about one-half that of air.

The method of dimensions does not tell us the numerical value of the constant K. The magnitude of this constant has been determined by towing boards in water (Froude),(1) by rotating disks of metal in water (Unwin),(4) and by many measurements of the flow of water in pipes. All of these experiments give values which may be summarized approximately as follows:

$$\left.\begin{array}{l}\text{Smooth varnished surface, } K=0.001\\ \text{Very coarse sand surface, } K=0.005\end{array}\right\} \tag{12}$$

Tests on the flow of air and illuminating gas in pipes lead to approximately the same range of values, depending on the character of the surfaces. From our experiments we can obtain a rough idea of the value of this constant K even though the apparatus was not designed for this purpose. Thus if we assume the average active surface of the cylinder B to be 1 cm. wide, we obtain $K=0.009$ which is of the same order of magnitude as the values previously stated.

In most rotating machinery the velocities are well above the critical value so that turbulent flow can usually be assumed. Cases will arise where the windage loss is a combination of turbulent and non-turbulent flow. For example, in a large rotating disk the linear velocity would increase from the shaft outwards and we might find stream line flow near the shaft with turbulent flow starting part way out.

In practice, due to the difficulty of making accurate calculations, it will generally be sufficient to assume a mean velocity and consider the motion turbulent.

We can now write the power expended in windage loss as follows:

$$W = K A \rho v^3 \text{ dyne-cm. per sec.}$$

or

$$W = K A \rho v^3 \times 10^{-7} \text{ watts} \tag{13}$$

where K = 0.001 to 0.005
A = Area of surface in sq. cm.
ρ = Density of gas or liquid in grams per c.c.
v = Average velocity of fluid relative to the surface in cm. per sec.

For convenience in calculation, equation (13) may be written

$$W = K\ A\ \rho\ v^3 \text{ kw.} \qquad (14)$$

where K = 0.001 to 0.005

A = Area of surface in sq. meters

ρ = Density of fluid in gm. per c.c.

v = Average velocity of fluid relative to the surface in meters per second

If we apply the constant $K = 0.005$ for ordinary rough surfaces, and assume air at 25 deg. C., and 76. cm. Hg, for which $\rho = 0.00118$ grams per c.c., we obtain

$$W = 0.005 \times 0.00118\ A\ v^3 \text{ kw.}$$

$$W = 5.9\ A\ v^3 \times 10^{-6} \text{ kw.} \qquad (15)$$

In Fig. 6 the kilowatt loss per square meter of surface is plotted against the assumed peripheral velocity for several different gases.

In large electrical machines the convection caused by the rotor is usually insufficient for cooling purposes and the circulation is assisted by a centrifugal fan which may either be incorporated as a part of the rotor or installed as an auxiliary piece of apparatus.(21) For the small pressure differences here met, the cooling gas is generally treated as an incompressible fluid or, what is the same thing, its density is considered to remain constant during its flow through the machine. The power supplied by the fan is then merely that necessary to force the required quantity of gas through the machine passages, and may be written as follows:

$$W = p\ Q\ \frac{\text{dynes}}{\text{sq. cm.}} \times \frac{\text{cu. cm.}}{\text{sec.}} \qquad (16)$$

where p = Pressure difference required to force the fluid through the machine, in dynes per sq. cm.

Q = Quantity of gas or fluid in cu. cm. per sec.

For convenience in calculation this may be written as

$$W = 0.0981\ p\ Q \text{ kw.} \qquad (17)$$

where p = Pressure difference in cm. of water

Q = Flow in cu. m. per sec.

Now the pressure gradient required to deliver Q cu. cm. of gas through the machine may be found by considering two points in a pipe, l cm. apart, at which pressures P_1 and P_2 exist. (Fig. 7.) Then the work represented by this pressure difference p in dynes per sq. cm. is

$$w = p\frac{\pi d^2}{4}\ l \text{ dyne-cm.} \qquad (18)$$

where d = diameter of pipe in cm.

Now since the velocity remains constant and we have assumed no change in level, all of this energy must go into overcoming the resistance to flow in the length l of the pipe. The resistance for turbulent motion is assumed to be that given by equation (11) so that the work done in overcoming this force through the distance l will be

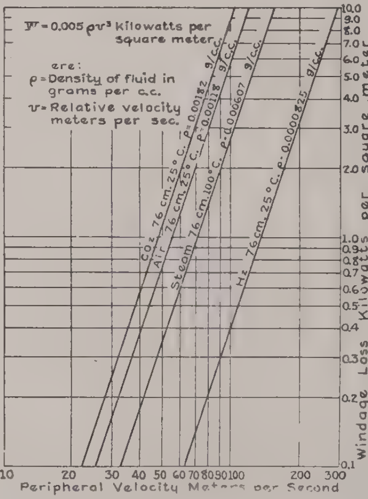

Fig. 6. Windage Loss in Kilowatts Per Square Meter for a Rotating Machine Immersed in Various Gases

$$w = f \times l = K\ A\ \rho\ v^2 \times l \text{ dyne-cm.} \qquad (19)$$

where $A = \pi d \times l$ = Area of the surface under consideration.

Equating the two expressions for work,(22) we have

$$\frac{p}{l} = \frac{4K\ \rho\ v^2}{d} \qquad (20)$$

Substituting $Q = \frac{\pi d^2}{4}\ v$ cu. cm. per sec., then

$$\frac{p}{l} = \frac{64\ KQ^2 \rho}{\pi^2\ d^5} \qquad (21)$$

From equation (21) we see that the pressure difference required in a given machine for a given quantity of flow Q will be proportional to the density of the gas. Therefore, the power required for the circulation of a given quantity of gas will also be proportional to the density, by equation (16).

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(21) Edgar Knowlton, "Ventilation as a Factor in the Economical Design of Electrical Machinery," G. E. Rev., pp. 406, 595, May, July, 1916.

E. Knowlton and E. H. Freiburghouse, "Ventilation Systems for Steam Turbine Alternators," G. E. Rev., pp. 240, 367, Apr., May, 1918.

(22) This is the Chezy formula for the flow in pipes which is usually written as:

$$\frac{d}{4}\frac{h}{L} = \zeta\frac{v^2}{2g} \quad \text{See Unwin ``Hydraulics,'' p. 153.}$$

This is the same as above if we change to c.g.s. units and note that $h = \frac{p}{\rho}$, also $\zeta = 2K$.

(23) Loewenstein, "Centrifugal Air Compressor," G. E. Rev., Vol. XV, 1912, p. 139.

Now the theoretical pressure rise in a centrifugal pump, with properly shaped discharge vanes to convert the tangential exit velocity into useful pressure, is given by(23)

$$p = \eta \, \rho \, v^2 \text{ dynes per sq. cm.} \qquad (20)$$

where η = Hydraulic efficiency (50 to 75 per cent)
ρ = Density of fluid gr. per c.c.
v = Peripheral velocity cm. per sec.

From this we see that assuming equal hydraulic efficiencies for a centrifugal fan working in different gases, the pressure developed will be proportional to the density of the gas and, as we have seen, this will lead to a fixed quantity of circulation in a machine of given design. If is therefore apparent that with a given machine the substitution of different gases will not alter the quantity or velocity of the circulation, but will result in a windage loss proportional to the density of the gas.

We may now make an estimate of the windage loss for a large turbine generator[24] as follows:

Rotor length = 3.15 meters (approx.)
Rotor diameter = 1.14 meters (approx.)
R.p.m. = 1800
Peripheral velocity = 107 m. per sec.
Area of rotor = 11.3 sq. m. (approx.)
Average axial velocity of forced circulation = 51 m. per sec.
Resultant air gap velocity = $\sqrt{107^2 + 51^2}$ = 119 m. per sec.
Rotor surface windage loss from Fig. 6 or equation (15) = 10 × 11.3 = 113 kw.

We must now add to this the power required by the fan to circulate the air. For this machine the air circulation is approximately 1000 cu. ft. per sec. against a pressure of 14 in. of water. We then have from equation (17)

$$W = 0.0981 \times 35.6 \times 28.3 = 99 \text{ kw.}$$

If we now assume a hydraulic efficiency of approximately 50 per cent for the fan, we obtain by adding the surface and fan consumption:

Total windage loss = 311 kw. (approx.)
Observed windage loss = 325 kw.

The total windage loss for this same machine in pure hydrogen at atmospheric pressure would be approximately 32 kw., or in the ratio of the densities.

Summary

(1) Under the conditions of direct or stream-line flow, the frictional resistance in gases and liquids is determined by the viscosity. For the case of parallel planes immersed in a fluid, we have the familiar relation:

$$f = \frac{A \, \mu \, v}{l} \text{ dynes}$$

where A = Area of surface in sq. cm.
μ = Viscosity of gas or liquid in c.g.s. units
v = Relative velocity between surfaces in cm. per sec.
l = Distance between surfaces in cm.

(2) Under the conditions of turbulent flow, the frictional resistance in gases and liquids is determined by the density only.

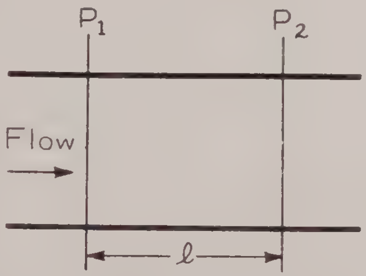

Fig. 7. Conditions of Gas Flow in a Pipe

The same law which applies to both gases and liquids may be written

$$f = K \, A \, \rho \, v^2 \text{ dynes}$$

where K = 0.001 to 0.005 depending on the roughness of the surface
A = Area of surface in sq. cm.
ρ = Density of gas or liquid in gm. per c.c.
v = Relative velocity between surface and liquid in cm. per sec.

(3) The fact that the same numerical constant K applies to resistance in liquids and gases is of considerable interest. This constant also appears as an important factor in heat convection.

(4) The windage loss for a machine of given design, fan dimensions, etc., will have a total value proportional to the density of the gas in which the machine is operating.

(5) For the same fan dimensions and speed, the velocity of circulation and therefore the quantity of flow through a given machine is independent of the density of the gas.

Acknowledgment is made to Dr. W. R. Whitney for suggesting the investigation, and to Mr. E. W. Kellogg for suggestions relative to the design of apparatus. Valuable assistance was also rendered by Mr. E. P. Lawsing in connection with the experiments.

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[24] The machine chosen is of the horizontal, four-pole, revolving-field type, and is rated at 31,250 kv-a., 1800 r.p.m., 13,200 volts.

A Study of Crystal Structure and Its Applications

PART V*

THE BRAGG METHOD OF CRYSTAL ANALYSIS (Cont'd)

By W. P. Davey
Research Laboratory, General Electric Company

In this installment of the series on crystal structure, the author completes his discussion of the Bragg method of x-ray analysis. In Part IV, it will be remembered, he described the Bragg apparatus and demonstrated the successive steps of the theory on which it is based. In the present article Dr. Davey shows the working of the Bragg method in determining the structure of the halides of sodium and potassium, and of other common crystalline compounds.—Editor.

The Structure of the Common Alkali Halides

So far, the Bragg method has been described only in general terms. Specific examples have been given only when necessary to make some special point clear or to justify some particular assumptions. The method as a whole will now be illustrated by specific examples. Since, historically, the structures of the common alkali halides were first determined by the Bragg method, it will be of interest to take them up first, using as typical examples NaCl, KCl, and KI. These compounds are composed of equal numbers of atoms (or more correctly, ions) of an alkali metal and a halogen. From their external symmetry they are all classed as cubic crystals.

When a single crystal of KCl is examined by the Bragg method, it is found that the plots indicate a marshalling of diffracting centers at the corners of a simple cubic lattice-work. Although the plots assign a simple cubic structure to KCl, they do not show whether a whole "molecule" of KCl is to be found at each corner of the unit-cube, or whether half the corners will contain K^+ and half Cl^-. In either case, equations (40) and (41) would give identical answers for any family of planes, for the ionic numbers of K^+ and Cl^- are identical. We may, therefore, assume that the ratios of the intensities of different orders of diffraction will be practically identical no matter which family of planes is investigated. This is borne out by experiment, and these ratios are therefore called the "normal rate of decline" of intensity with order of diffraction. As has been stated before, it is approximately

First order: second order: third order = 100 : 18.7 : 6.25.

The Bragg plots use only the first order diffracted beam. They show a face-centered cubic marshalling of diffracting centers for NaCl and for KI. For the 1 0 0 and 1 1 0 planes of both these salts the intensities of the first three orders of diffraction tend to follow the same "normal" law of decline as the planes of KCl.

For instance, the intensity of diffraction from the 1 0 0 planes of NaCl is (49)

1st order ----- 100.00
2nd order ----- 19.90
3rd order ----- 4.87
4th order ----- 0.79
5th order ----- 0.116

For the 1 1 0 planes it is, in the same units,

1st order -- 50.4 -- 100 per cent
2nd order -- 6.10 -- 12 per cent
3rd order -- 0.71 -- 1.4 per cent

This indicates that the 1 0 0 and 1 1 0 planes are composed of equal numbers of alkali and halogen ions. Otherwise these planes would not show the "normal" rate of decline as nearly as they do.

The 1 1 1 planes of NaCl and KI, however, do not follow this "normal" law. For NaCl, the intensities expressed in the same units as before are

1st order -- 9.00 -- 100 per cent
2nd order -- 33.1 ----------- 100 per cent
3rd order -- 0.58 -- 6.4 per cent
4th order -- 2.82 ----------- 8.5 per cent
5th order -- 0.137 --- 1.5 per cent

The odd orders alone or the even orders alone from the 1 1 1 planes have a rate of decline comparable to that of the successive orders of

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(49) W. L Bragg, R. W. James, C. H. Bosanquet, *Phil. Mag.* *41*, 309 (1921).

*References made to material hitherto published in this series of articles may be readily located from the following table:

Issue	Figs.	Equations	Tables	Footnotes
Part I, Nov., 1924; p. 742	1 and 2	1 to 16	I and II	1 to 21
Part II, Dec., 1924; p. 795	3 to 10	17 to 32	III	22 to 27
Part III, Feb., 1925; p. 129	11 to 22	33 to 37	IV	28 to 42
Part IV, Apr., 1925; p. 258	23 to 28	38 to 41	None	43 to 48

diffraction from the 1 1 0 planes. This indicates that the 1 1 1 planes of NaCl (and the same thing holds with KI) occur in pairs, the Bragg plots showing only the locations of the planes containing the ions of higher atomic number in each case.

All these conditions are satisfied if we assume that NaCl and KI each have a simple cubic structure in which alkali and halogen ions occupy alternate corners as in Fig. 29. Such a structure places each kind of ions on a face-centered cubic lattice. The simple cube is obtained by the interpenetration of the two face-centered lattices. Each of the 1 0 0 and 1 1 0 planes if extended to infinity is composed of equal numbers of alkali and halogen ions. The 1 1 1 planes occur in alternate layers of alkali and halogen ions. Because of the close similarity of NaCl, KCl, and KI in physical and chemical properties, and because of the similarity in their crystal habits, we are at once tempted to assume that KCl has an arrangement of ions in space like that assigned to NaCl and KI. Because the K^+ and Cl^- ions have equal ionic numbers, and therefore approximately equal diffracting powers, the two face-centered cubes of K^+ and Cl^- would be indistinguishable from each other, so that the effect, as far as the diffraction of x-rays is concerned, would be that of a simple cubic lattice.

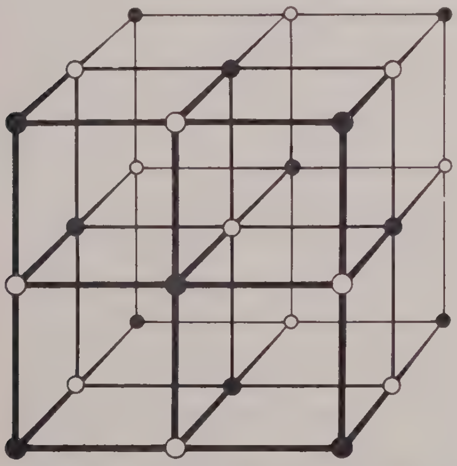


Fig. 29. Structure of Unit-cube of NaCl, KCl and KI. Dark circles represent the alkali ion, light circles represent the halogen ion

If the structures assumed above are correct, they must be consistent with the known densities of the three salts. In Part I the wavelength of Mo_K alpha was calculated in terms of the density of NaCl and the structure given above. Using this value of the wavelength the sides of the unit simple cubes of KCl and KI are found experimentally to be ⁽⁴¹⁾ 3.138 ± 0.003 A and 3.525 ± 0.004 A respectively. The density of KCl must equal the mass of its unit simple cube divided by the volume of that cube (see equation 30). Since K^+ and Cl^- occupy alternate corners of the cube, the *average mass* per crystallographic point must be used, i.e., $\frac{39.10 + 35.46}{2} \times 1.649 \times 10^{-28}$ grams. This gives a density of 1.990 ± 0.006 as compared with 1.987 determined in the usual way. A similar calculation gives the density of KI as 3.125 ± 0.009 as compared with 3.123 determined in the ordinary way. The agreement is within the experimental error. This, together with the fact that all other methods of crystal analysis lead to the same structure for these salts, gives such a high degree of probability to the solution that any objection to its correctness must be regarded as purely academic.

A warning should be given against assuming that, just because the crystals of two chemically similar substances both belong to the cubic system, the substances have the same crystal structure. For instance, all the alkali halides have physical and chemical similarities, and they all belong to the cubic system. Of these, CsI, CsBr, and CaCl crystallize as body-centered cubic lattices of ions. CsF and all the Rb-, K-, Na-, and Li-halides crystallize as simple cubic lattices of ions. The ammonium halides may have either of these structures depending upon the temperature. It is therefore evident that in every case the results of x-ray diffraction must be shown to be similar before any weight can be placed upon physical, chemical, and crystallographic similarities.

The Structure of Diamond, Zinc Blende and Fluorite

Just as a correlation of the diffraction patterns of NaCl, KCl, and KI served to give the key to the interpretation of all three, so the structure of diamond, zinc blende (sometimes called sphalerite, ZnS) and fluorite (CaF_2) are best considered together. The diffraction patterns of the 1 0 0, 1 1 0, and 1 1 1 planes of the first two of these crystals are shown diagrammatically in Fig. 30⁽¹⁾. The 1 0 0 and 1 1 0 planes of diamond show a progressive decrease in the intensity of successive orders of diffraction which is much like the "rate of normal decline." The pattern from the 1 1 1 planes is of the same general sort except that the second order is almost entirely absent. The intensities are, approximately,

1 0 0 planes.
1st order – 8 – 100 per cent
2nd order – 2 – 25

1 1 0 planes.
1st order – 12 – 100 per cent
2nd order – 2½ – 21
3rd order – 1 – 8

1 1 1 planes.
1st order – 24 – 100 per cent
2nd order – 0 – 0
3rd order – 4 – 17
4th order – 1¾ – 7
5th order – 0¾ – 3

The Bragg plot shows the diamond crystal to be of the face-centered cubic type. Assuming all the atoms in diamond to be alike, we must account for the absence of the second order diffraction from the 1 1 1 planes in terms of the marshalling of the atoms in space. This means that in equation (41) N_A and N_B are the same, and we must find a value for $1/m$ such that the intensity for the second order will come out to be zero. In other words $\cos\frac{4\pi}{m}$ must be -1; that is, $\frac{4\pi}{m}=180^0$, and $1/m=1/4$. We now have to imagine a face-centered cubic crystal structure such that the 1 1 1 planes come in pairs, the members of a pair being one fourth as far apart as the corresponding planes of two successive pairs (see Fig. 26). Such a structure has already been shown in Figs. 7 and 8.

Each order of diffraction for the 1 0 0 and 1 1 0 planes is less intense than the next lower order, so that in a qualitative way these planes follow the "rate of normal decline." The agreement is, however, far from quantitative. This might possibly be explained by the conditions of the experiment, as in the case of the two sets of experimental values cited above for the intensities of diffraction from the 1 1 1 planes of NaCl, or it might be explained in terms of the configuration of the electrons in the carbon atom. In any case, Bragg's interpretation of the structure of diamond, as it is described above, is consistent with the ordinary crystallographic properties of diamond and with its density. The structure has since been confirmed by both the Laue and the Powder methods, and is as well established as any crystal structure so far investigated.

The Bragg plot (which, it will be remembered, uses only the first order diffraction) shows zinc blende to be founded on a face-centered cubic lattice. The intensities of the different orders of diffraction are shown in Fig. 30. They are not those to be expected from equation (41) for an ordinary face-centered cube. The density shows that, considered only as a face-centered cube, a whole "molecule" of ZnS must be associated with each point. This is interpreted to mean that the ions of Zn^{++} are arranged on a face-centered cubic lattice, and that we must find additional places in this lattice-work for the S^{--} ions. If we place the Zn^{++} ions on a face-centered cubic lattice, there are two simple ways of symmetrically placing an equal number of S^{--} ions, either of which places the S^{--} on a second face-centered cubic lattice. In the first way the two face-centered cubic lattices are displaced with respect to each other along a cube axis so that the corners of the S^{--} cube come at the centers of the edges of the Zn^{++} cube. This is the structure already found above for NaCl, KCl, KI, etc., and illustrated in Fig. 29. In the second way, the two face-centered cubes are displaced with respect to each other along the body-diagonal, so that the corners of the S^{--} cube come one fourth of the way along the body-diagonal of the Zn^{++} cube. This is the structure already

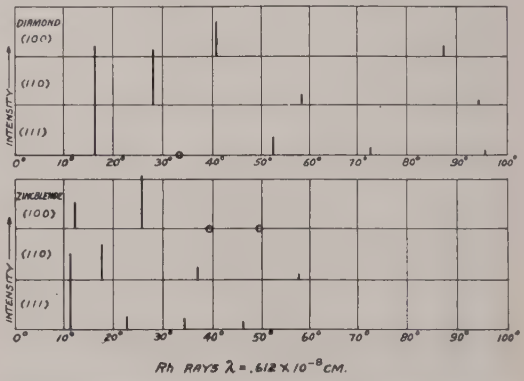


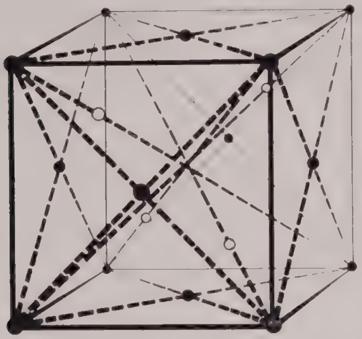
Fig. 30. Intensities of Different Orders of Diffraction from 1 0 0, 1 1 0, and 1 1 1 Planes of Diamond and Zinc Blende. (After Bragg)

found for diamond, and illustrated in Figs. 6, 7, and 8. We must make a choice between these two structures for zinc blende, and the choice is to be made on the basis of the relative intensities of the different orders of diffraction for the various planes of atoms in the crystal. The intensities shown in Fig. 30 are approximately,

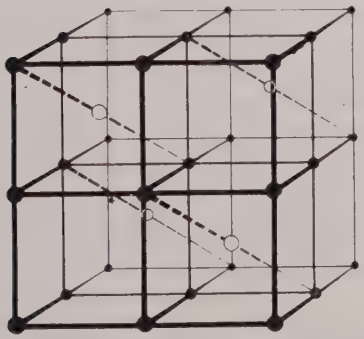
1 0 0 planes, –
  1st order – – 6
  2nd order – – 12
  3rd order – – 0
  4th order – – 0

1 1 0 planes.
  1st order – – 7
  2nd order – – 3
  3rd order – – 1

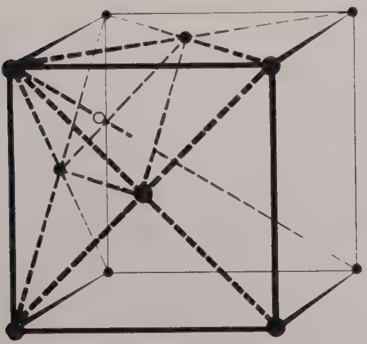
1 1 1 planes.
  1st order – – 17
  2nd order – – 2½
  3rd order – – 2½
  4th order – – 1



(*A*) Showing how the structure of zinc blende is related to that of diamond (Fig. 7)



(*B*) Showing how the S^{--} may be considered to be at the body-centers of four out of a possible eight construction cubes built into the face-centered cube of Zn^{++}



(*C*) Showing how the S^{--} may be considered to be at the center of a tetrahedron of Zn^{++}

Fig. 31. Structure of Unit Cube of Zinc Blende (ZnS). Dark circles represent the Zn^{++}, light circles represent the S^{--}

It is at once evident that for the first and third of the three families of planes cited, these intensities do not correspond at all with those for the same family of planes in NaCl. The intensities of the various orders of diffraction from the 1 0 0 planes are like those of the 1 1 1 planes of NaCl. It has already been shown in the discussion of equation (41) that they are what might be expected of alternate layers of Zn^{++} and S^{--}. This is consistent with the second of the two tentative structures given above for zinc blende, which is brought out more clearly in Fig. 31. The construction lines show that each S^{--} ion lies at the center of a tetrahedron of Zn^{++} whose vertex is the corner of the face-centered cube of Zn^{++} and whose base is determined by the three Zn^{++} ions of the centers of the adjacent faces. Such a structure causes the S^{--} ions to form 1 0 0 planes midway between the 1 0 0 planes of Zn^{++}, in this way reducing by interference the intensity of the *odd* orders of diffraction. It introduces no new 1 1 0 planes, so that the various orders of diffraction from 1 1 0 tend to show the "normal rate of decline." It gives 1 1 1 planes of S^{--} close to similar planes of Zn^{++}, so that the distance between S^{--} and Zn^{++} planes is one fourth that between the nearest Zn^{++} planes. It will be remembered that this type of lattice caused the 1 1 1 planes of diamond to lose their second order diffraction, for the two sets of planes had equal diffracting power. Since the S^{--} has less diffracting power than Zn^{++}, the second order diffraction of the 1 1 1 planes of zinc blende is not entirely wiped out, but is so greatly weakened that it is no more intense than the third order.

The relative intensities of the various orders of diffraction from the 1 0 0, 1 1 0, and 1 1 1 planes of fluorite (CaF_2) are practically identical with those for diamond. Here again the Bragg plot, founded on interplanar distances calculated from first order diffractions, indicates a face-centered cubic structure. The density shows that we are to place the Ca^{++} on the points of this face-centered cubic lattice, and find other, symmetrically located, positions in the lattice for 2 F^- such that the intensities of the various orders of diffraction may be accounted for. Since the cleavage is just like that of diamond, we shall at once try the diamond type of lattice, putting the F^- at the centers of tetrahedra of Ca^{++}. In order to get enough F^- into the lattice to conform to the chemical formula CaF_2 all these tetrahedra must contain F^-. This gives 1 0 0 planes composed alternately of Ca^{++} and 2 F^-. Since the ionic number of Ca^{++} is $20-2=18$ and the ionic number of F^- is $9+1=10$, it is evident that the sum of the diffracting powers of the F^- planes is very nearly the same as that of the Ca^{++} planes. The relative intensities of the various orders of diffraction from the 1 0 0 planes should therefore be practically the same as in diamond. The 1 1 0 planes are composed of both Ca^{++} and F^- so they tend to give the "normal rate of decline" as in diamond. The 1 1 1 planes have a plane of F^- on each side of each plane of Ca^{++}, and situated one fourth as far from it as the next plane of Ca^{++}. This means that there are two F^- planes between each two Ca^{++} planes, and that the distance between the two F^- planes is half that between adjacent Ca^{++} planes. The result is that the second order diffraction from the Ca^{++} planes is almost completely destroyed by interference with the first order beam from the two F^- planes. The relative intensities of the diffracted beams from the 1 1 1 planes are therefore practically the same as in diamond. The structure of fluorite just described is shown in Figs. 32 and 33.

The Structure of the Calcite Group

The Bragg plot for calcite (Iceland spar, $CaCO_3$) shows it to be a face-centered rhombohedral lattice. A rhombohedron may be considered to be a cube which has been stretched or compressed along the direction of one of its body-diagonals. Although the angles between the three axes are all equal, they are no longer 90 deg. If the body-diagonal of the cube has been stretched, these angles are less than 90 deg. If it has been compressed they are more than 90 deg. For calcite the angle between any two axes of reference is 101 deg. 54 min. The Bragg plot gives the data for a rhombohedron directly in terms of these trigonal axes so that in the following discussion these axes will be employed rather than the axes of the hexagonal system. See equations (28) and (29).

In a face-centered cube the distance between successive 1 0 0 planes is one half the side of the unit cube because the atoms at the centers of the faces introduce planes half way between the faces of the cube. Similarly the interplanar spacing d_{100} ($=3.03\times10^{-8}$ cm.) of the face-centered rhombohedron is half the side of the unit rhombohedron. The density of calcite, measured in the usual way, is 2.71. This density is consistent with a structure for calcite in which a whole "molecule" of $CaCO_3$ is associated with each point of a face-centered rhombohedral lattice. Using a precise determination of the density of a particular sample of calcite, A. Compton (11) finds for that sample that $d_{100}=3.028\times10^{-8}$ cm. This value has since been confirmed by Birge(11), and is the value which is universally accepted as the primary standard for all crystal structure and wavelength work. Just as, in the case of NaCl, it was necessary to find the location of Na^+ in the lattice in terms of the intensity of the various orders of diffraction, so in the

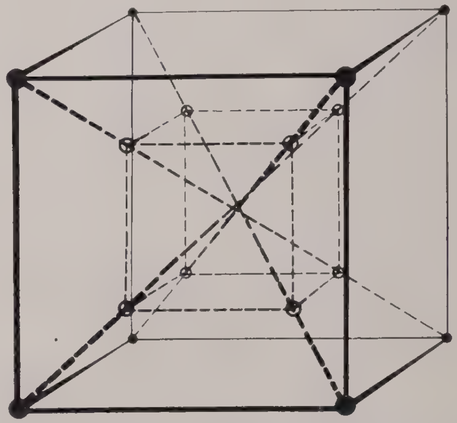


Fig. 32. Inner Structure of Unit-cube of Fluorite (CaF_2). The light circles in this figure represent F^-. The Ca^{++} is on a face-centered cubic lattice like Fig. 7. When these two figures are superimposed to give the complete structure of fluorite, we have Fig. 33

case of calcite we assume from the Bragg plot that the CO_3^{--} radicals (ionic number 32) are marshalled on a face-centered rhombohedral lattice and we assign places in that lattice to the Ca^{++} (ionic number 18) in terms of the relative intensities of the diffracted beams. As in the case of NaCl, the various orders of diffraction from the 1 0 0 and 1 1 0 planes tend to show the "normal rate of decline" of intensity, indicating that these planes contain equal numbers of Ca^{++} and CO_3^{--} ions. For the 1 1 1 planes the relative intensities are approximately

1st order — 9
2nd order — 29
3rd order — 0
4th order — 6

showing that these planes are made up alternately of Ca^{++} and CO_3^{--}.

Bragg has pointed out ⁽¹⁾ that if this is the case it should be possible to find a carbonate which will show a simple rhombohedral structure of ions on a Bragg plot, just as KCl shows a simple cubic structure of K^+ and Cl^-. The ionic numbers of the positive and negative ions of a series of salts having the calcite structure are

Na : NO_3 -- 10 : 32
Ca : CO_3 -- 18 : 32
Mn : CO_3 -- 23 : 32
Fe : CO_3 -- 24 : 32

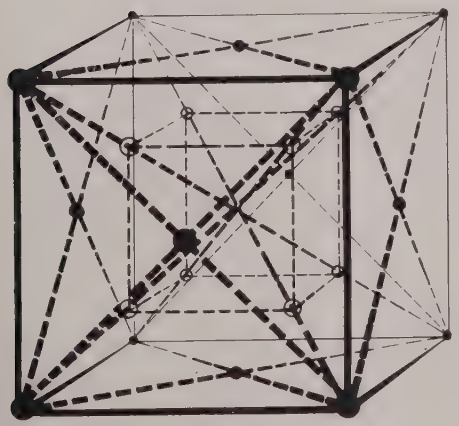


Fig. 33. Structure of the Unit-cube of Fluorite, (CaF_2). Dark circles represent Ca^{++}; light circles represent F^-

Bragg's experimental data for diffraction from the 1 1 1 planes of these salts are given in Fig. 34. It is evident from this figure that the nearer the two ions are in ionic number the more nearly equal are their diffracting powers. For $NaNO_3$ the preponderance of x-ray intensity from the NO_3^- is so great that the intensity of the first order of diffraction is greater than that of the second order. For $MnCO_3$ and $FeCO_3$ the interference is so nearly complete that the first order diffraction is practically extinguished. If $ZnCO_3$ has a "calcite" structure, it should be an even better example, for its ionic numbers are 28 : 32. If the interference between Zn^{++} and CO_3^{--} turned out to be complete, the first order diffraction from the 1 1 1 planes would correspond to the distance between adjacent Zn^{++} and CO^{--} planes. This distance is half that between successive CO_3^{--} planes, so that the 1 1 1 spacings would appear to be half what they would have seemed if the interference between Zn^{++} and CO_3^{--} had not been complete. The Bragg plot for $ZnCO_3$ may therefore be expected to show a simple rhombohedral lattice just as for KCl it showed a simple cubic structure.

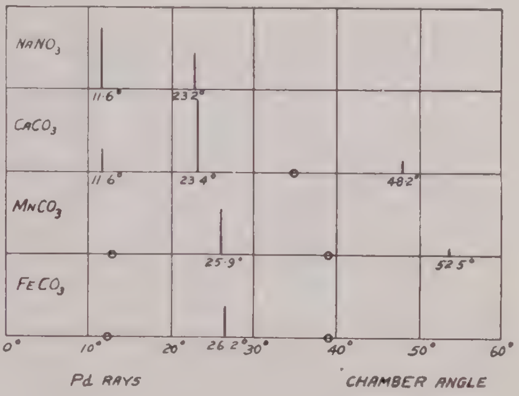


Fig. 34. Intensities of Different Orders of Diffraction from 1 1 1 Planes of $NaNO_3$, $CaCO_3$, MnCO and $FeCO_3$ (After Bragg)

We have now located the Ca^{++} and the CO_3^{--} radical in the calcite lattice. There remains the problem of showing the locations of the three oxygens with respect to the carbon. Bragg's solution to this problem, using intensity and symmetry considerations, is given in Fig. 35. The oxygens are placed at the corners of an equilateral triangle with the carbon at the center. In successive 1 1 1 planes of CO_3^{--} these triangles are rotated by 60 deg. In this way the average amount of oxygen along any one of the hexagonal axes is kept the same as along any other hexagonal axis, thus giving complete crystallographic similarity to each end of each axis. This not only gives a symmetrical crystal, but is also in accord with the fact that the etch figures are supposed to be identical on all 1 0 0 faces of a calcite crystal.

Purchasable Apparatus

Many university laboratories have built themselves duplicates of the Bragg apparatus. The photograph at the end of the previous installment of this series may be regarded as typical of this class of apparatus. Adam Hilger, Ltd., have put on the market a small Bragg apparatus designed by Dr. Müller. The diffraction pattern is recorded photographically, and the crystal is rocked slowly back and forth by a clock-work. A lead shield is provided to protect the photographic plate from stray x-rays. This apparatus may be set up in front of any x-ray tube having a suitable target material. Of course, any apparatus which is suitable for the Bragg method of crystal analysis can be used at once as an x-ray spectrometer for the determination of x-ray wavelengths.

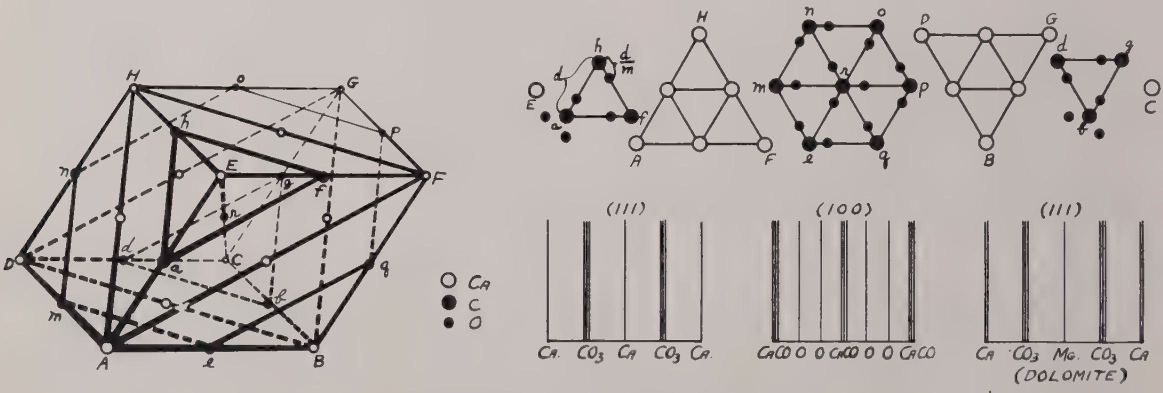


Fig. 35. Structure of Calcite (After Bragg)

The manufacturer of apparatus of this sort has, of course, no control over the use to which it is put by the purchaser. He cannot, therefore, be expected to guarantee the safety of the experimenter from exposure to x-rays. It is understood that in every case the experimenter must satisfy himself that the x-ray tube is properly surrounded by protecting material. Criteria for x-ray protection have been set up by the Protection Committee in England. The reader is referred to Kaye and Owen, *Proc. Phys. Soc. London*, *35*, 33 D, 1923. Corresponding criteria have been set up in this country and may be found in the U. S. Army x-ray manual. The writer's rule may be extreme, but at least if it errs it is on the right side. "If it is safe to store photographic materials without additional protection in the same room with the x-ray diffraction apparatus, then the apparatus is safe for the operator."

Summary of the Bragg Method

The Bragg method of crystal analysis may be summed up by saying that it interprets as much of the structure of a crystal as possible in terms of the angles of diffraction of x-rays of known wavelength, and in terms of the intensities of the diffracted beams. The nature of the method is such that the results are necessarily consistent with the symmetry of the crystal. The symmetry characteristics of the crystal are used as a primary tool in determining possible positions of atoms in the crystal only when x-ray methods are inapplicable.

(*To be continued*)

A Pan-chromatic Illuminated Fountain

An exceptionally beautiful illuminated fountain was recently presented to the mayor and citizens of Dallas, Texas, by its donor, Mr. R. A. Ferris. The fountain is centrally located in the Plaza before the railroad station, and consists of a main jet 75 ft. in height, which rises out of a nest of spray from several smaller jets in a central bowl and falls back upon itself illuminated by all the colors of the rainbow. The larger pool, with a diameter of 50 ft., is studded with dolphins delivering small jets also illuminated. The total effect, which is most beautiful, can only be surmised from the photograph, since it is the changing color scheme of the piece which gives it distinction.

The Ferris Illuminated Fountain in Dallas, Texas. Variable pan-chromatic lighting effects are produced upon the flying spray by powerful searchlights and an automatic mechanism of color screens

The idea of the pan-chromatic illumination of fountain jets was originated by the Illuminating Engineering Laboratory of the General Electric Company and bids fair to contribute largely to civic beauty. The method of obtaining strong colored illumination of the water jets is typified by the Dallas installation. The inner basin of the fountain is floored with plate glass and beneath this are located four incandescent-type searchlights aimed to play over the full length of the jet from all sides. Motor-driven color screens are placed above the searchlights and serve to turn the falling mist into an iridescent sheen of ever-changing color. The aggregate candlepower of these lights is 5,000,000, enough to bring even the most delicate shade of color into strong relief. The equipment room beneath the fountain is accessible by means of a tunnel connecting with a manhole. An attendant's regular services are not required, however, since the lights and screens operate automatically. The city of Dallas expects to illuminate the fountain every night in the year.

LIBRARY SECTION

Condensed references to some of the more important articles in the technical press, as selected by the G-E Main Library, will be listed in this section each month. New books of interest to the industry will also be listed. In special cases, where copy of an article is wanted which cannot be obtained through regular channels or local libraries, we will suggest other sources on application.

Armature Windings

Methods for Taking Data on Turbo-Generator Windings. A. C. Roe.
Ind. Engr., Apr., 1925; v. 83, pp. 178-181,209.

Balancing

Accurate Balancing of Machine Rotors. C. R. Soderberg.
Power Pl. Engng., Apr. 1, 1925; v. 29, pp. 388-389.

Circuit Breakers

Explosion of an Oil Circuit Breaker in the Pankow Converter Station. F. Schlemmer. (In German.)
Elek. Bahnen, Feb., 1925; v. 1, pp. 59-63.
(Illustrated account of causes and results.)

Oil Switch Designs; Application of Gas Chambers to High-Power Units. G. Scholl. (In German.)
Elektro-Jour., Feb. 25, 1925; v. 5, pp. 80-82.
(Illustrated account of Oerlikon designs.)

Electric Drive—Marine Auxiliaries

Electrically-Driven Auxiliaries on Board Ship.
Shipbuilder, Apr., 1925; v. 32, pp. 209-211.
(Describes the "Austin" system.)

Electric Locomotives

22,000-Volt Motor Generator Locomotives.
Engr., Mar. 20, 1925; v. 139, pp. 334-335.
(An illustrated account of the construction of locomotives for the Detroit & Ironton R. R.)

Electric Motors, Induction

New Type of Squirrel-Cage Induction Motor with High Starting Torque. T. F. Wall.
I. E. E. Jour., Mar., 1925; v. 63, pp. 287-298
(Presents the results of tests on a motor in which the compound-bar rotor conductors exhibit increasing resistance as the frequency is increased.)

Electric Transformers

Design of New Transformers to Operate in Parallel with Existing Transformers. S. Austen Stigant.
Elec. Rev., Mar. 6, 1925; v. 96, pp. 365-367.

Marking Transformer Terminals. W. G. Bass.
Elec'n, Mar. 20, 1925; v. 94, pp. 328-331.
("Practical advantages of a suitable system for three-phase equipment.")

Electricity—Applications—Agriculture

Rural Electrification in Pennsylvania. R. U. Blasingame.
Elec. Wld., Apr. 4, 1925; v. 85, pp. 713-715.
(Based on the author's report to the Pennsylvania Giant Power Survey.)

Fatigue of Metals

Studying the Fatigue of Metals. H. F. Moore.
Am. Mach., Apr. 9, 1925; v. 62, pp. 563-565.
(An illustrated account of methods and equipment employed at the University of Illinois in making tests under the auspices of several co-operating companies and societies.)

Gas Turbines

Internal-Combustion Turbine.
Motor Ship., Apr., 1925; v. 6, pp. 26-27.
(Abstracts of recent papers by W. J. Goudie and T. B. Morley.)

Heating

Heating and Ventilation of a Modern Steam Power Station. David S. Boyden and A. B. Williams.
Am. Soc. Heat. & Vent. Engrs. Jour., Apr., 1925; v. 31, pp. 231-246.

Insulating Oils—Testing

Effect of Moisture and Temperature on the Power-factor of Transformer Oil. J. E. Shrader.
Franklin Inst. Jour., Apr., 1925; v. 199, pp. 513-538.
(Presents results of tests.)

Locomotives, Turbo-Electric

Ramsay Condensing Turbo-Electric Locomotive. George F. Jones and T. Laurence Hale.
Mech. Engng., Apr., 1925; v. 47, pp. 235-242.
(An illustrated description.)

Measuring Instruments

Some New Electrical Instruments for Automotive Research. J. H. Hunt and G. F. Embshoff.
Soc. Auto. Engrs. Jour., Apr., 1925; v. 16, pp. 444-455.

Phototelegraphy

New Method of Transmitting Pictures by Wire or Radio. Charles C. Henry.
Radio Broadcast, May, 1925; v. 7, pp. 19-28.
(A review of the existing methods, and details of the Cooley system.)

Power Plants, Electric

"Somerset," Another Step Toward Super-Power.
Power Pl. Engng., Apr. 1, 1925; v. 29, pp. 368-376.
(Illustrated description of the Somerset Station of the Montauk Electric Co., near Fall River, Mass. Includes tabulated details of the equipment.)

Radio Engineering

Marconi Wireless-Beam Reflector on Inchkeith. N. Wells.
Engng., Mar. 13, 1925; v. 119, pp. 309-311.
(Illustrated description.)

Radio Transmitters

Wireless Telegraph Valve Transmitters Employing Rectified Alternating Current. G. Shearing.
I. E. E. Jour., Mar., 1925; v. 63, pp. 309-333.
(Describes the development of tube transmitters employing rectified power for use in naval communication.)

Shunts

Efficiency of End Connections, and the Short-Period Ratings of Large-Current Shunts. S. W. Melsom and H. C. Booth.
I. E. E. Jour., Mar., 1925; v. 63. pp. 299-303.

Steam Plants

Early Use of High-Pressure Steam.
Power, Mar. 24, 1925; v. 61, pp. 451-452.
(Tells of the Perkins high-pressure steam generator of 100 years ago.)

Testing Machines

Spring Testing Machine for Weighing and Repetition Tests.
Engng., Mar. 13, 1925; v. 119, p. 317.

Torsion Meters

Denny-Edgecombe Direct Vision Torsionmeter.
Engng., Mar. 20, 1925; v. 119, pp. 345-349.
(Illustrated description.)

Vision

Effect of Brightness of the Precision of Visually Controlled Operations. Percy W. Cobb and Frank K. Moss.
Franklin Inst. Jour., Apr., 1925; v. 199, pp. 507-512.
(Results of tests to determine certain relations between illumination and the work produced under its effect.)

Voltage Regulation

Voltage Regulation by Static Transformers. G. Rattenbury.
Elec. Rev., Apr. 3, 1925; v. 96, pp. 524-527.

Water Turbines

High-Specific-Speed Hydraulic Turbines.
Mech. Engng., Apr., 1925; v. 47, pp. 285-287.
(From a symposium of six papers presented before the A.S.C.E.)

Welding

Welding vs. Riveting of Large Structures. W. Spraragen.
Iron Age, Apr. 9, 1925; v. 115, pp. 1051, 1095-1096.

X-Rays

X-Ray Investigation of Steel Castings for Advanced Steam Conditions. F. H. Morehead.
Power, Apr. 7, 1925; v. 61, pp. 520-522.

NEW BOOKS

Alternating Current Rectification. L. B. W. Jolley. 352 pp., 1924, N. Y., John Wiley & Sons.

Atmosphärische Störungen in der Drahtlosen Nachrichtenübermittlung. A. Koerts. 151 pp., 1924, Berlin, M. Krayn.
(The first of a series of papers in German, edited by Dr. Eugen Nesper, on high frequency phenomena. The present one, on atmospheric disturbances in wireless communication, takes up the theory of oscillating systems, general considerations of atmospheric disturbances, the effect of coupled circuits in preventing interference, and beam transmission.)

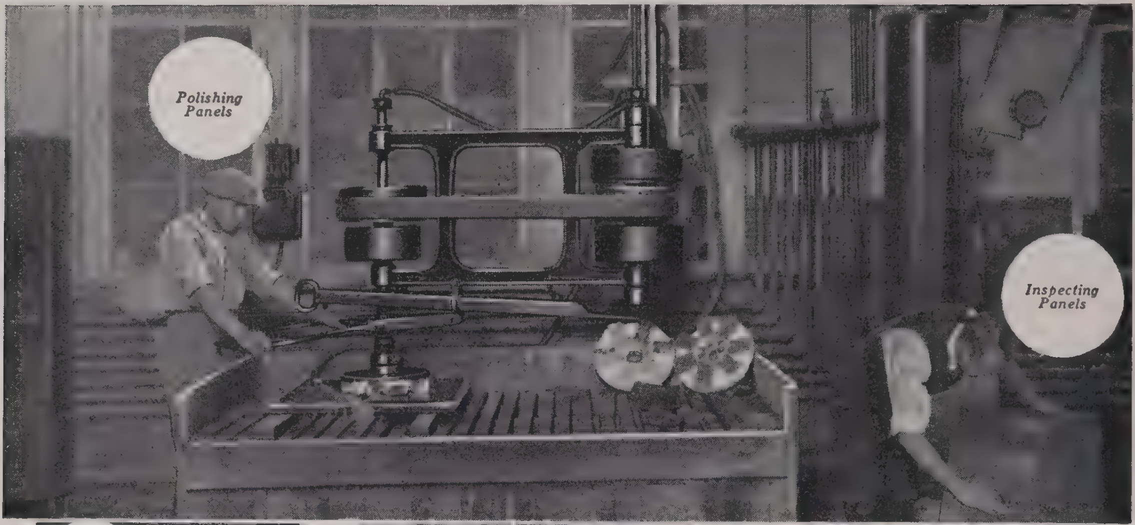
Electrical Design of Overhead Power Transmission Lines. William T. Taylor and R. E. Neale. 266 pp., 1925, N. Y., D. Van Nostrand Co.
(Deals primarily with the electrical design of lines 50 or 60 miles long and operating at voltages up to 50 or 60 kilovolts. Special effort has been made to present the subject in a quantitative manner so that the information may be directly applicable to practical design. Only elementary mathematics is employed. Numerous charts and tables adapted for immediate use in actual design work are presented. Numerical examples illustrating the methods and quantities discussed in the text are freely interspersed. The result is a volume which should prove very useful to the designer of transmission lines of medium lengths and voltages.)

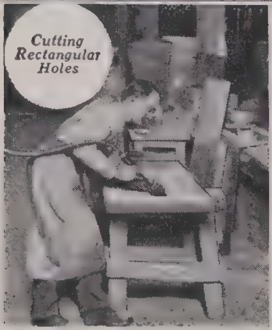
Leçons d'Électricité. Vol. 1. Éric Gérard. (New ed. revised by Léon Bouthillon.) 509 pp., 1925, Paris, Gauthier-Villars et Cie.
(The first part of a four-volume work intended to form a complete treatise, in French, on electrical engineering. This first volume treats the fundamental laws of electricity and magnetism, and electric and magnetic measurements.)

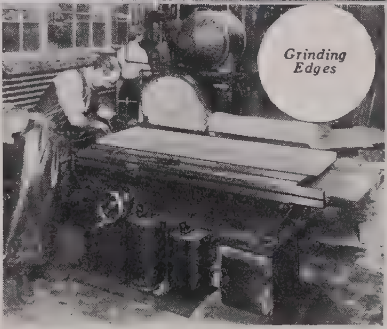
Popular History of American Invention. Waldemar Kaempffert. 2 vols., 1924, N. Y., Charles Scribner's Sons.

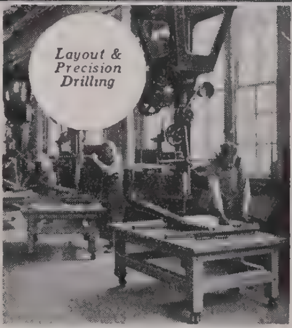
Principles of Transmission in Telephony. M. P. Weinbach. 303 pp., 1924, N. Y., Macmillan Co.
(Presents a rigorous mathematical analysis of the problems encountered in telephone practice. After introductory chapters on harmonic and hyperbolic functions, the author takes up electric wave propagation, open-circuited and short-circuited lines, lines with end impedance, energy transfer, power relations, equivalent circuits, distortion, inductive loading, amplifiers, line impedance, and transmission equivalents. A bibliography of fifty-six entries is appended. The volume constitutes a text for students interested in the more advanced theory of telephone engineering.)

Profitable Science in Industry. Dwight T. Farnham and others. 291 pp., 1925, N. Y., Macmillan Co.









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Starting with the slate as received from the quarry, dielectric-strength and leakage tests are made on every lot. To secure accuracy, the panels are laid out with individual templates. Precision drilling is accomplished with special tools, and with jigs for correct alignment. An unblemished surface is assured by polishing *after* the panels are drilled.

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22A-68

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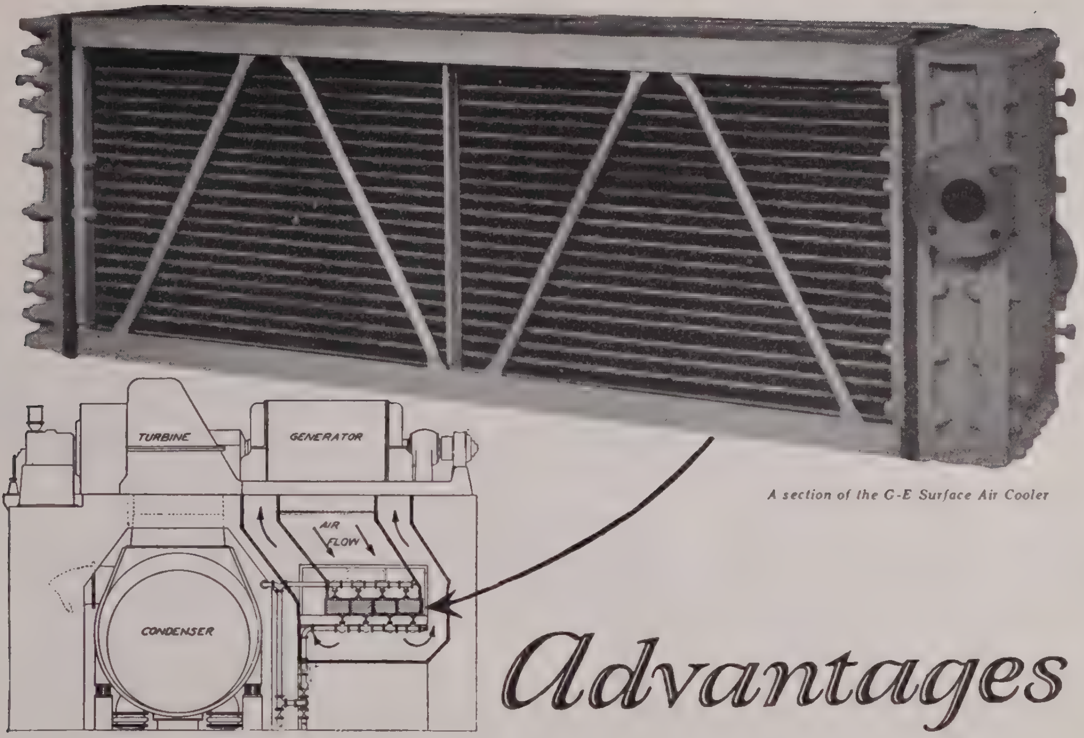

A section of the G-E Surface Air Cooler

Advantages

Use the closed system of ventilation and profit by these advantages

Generator protection—the closed system of ventilation using only clean, dry air.

Less fire hazard—because the volume of air in this system can support but little combustion.

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The cooler can be paralleled with the condenser circulating system—giving a reliable and inexpensive water supply, without the need for an additional pump.

A minimum volume of water is required—of value where water supply is limited.

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The General Electric generating equipment going into modern plants today includes Air Coolers for their closed system of generator ventilation. More than a million kw. have been installed. Write for further information.

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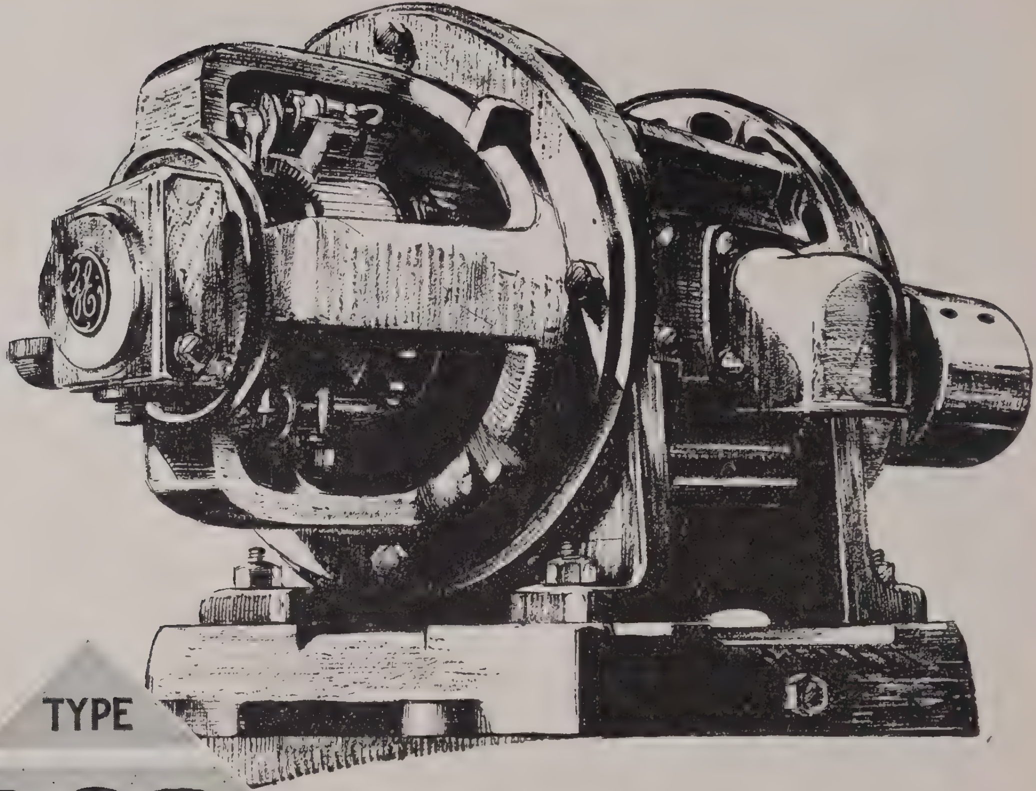

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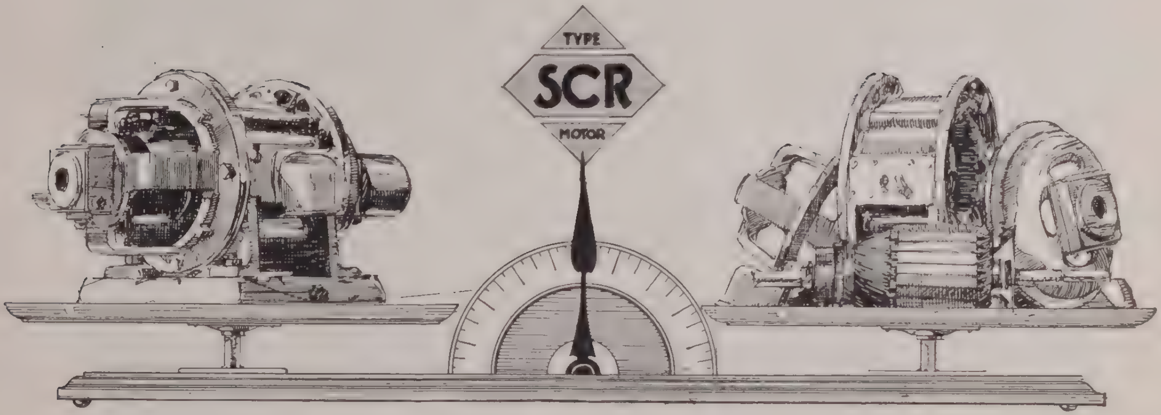

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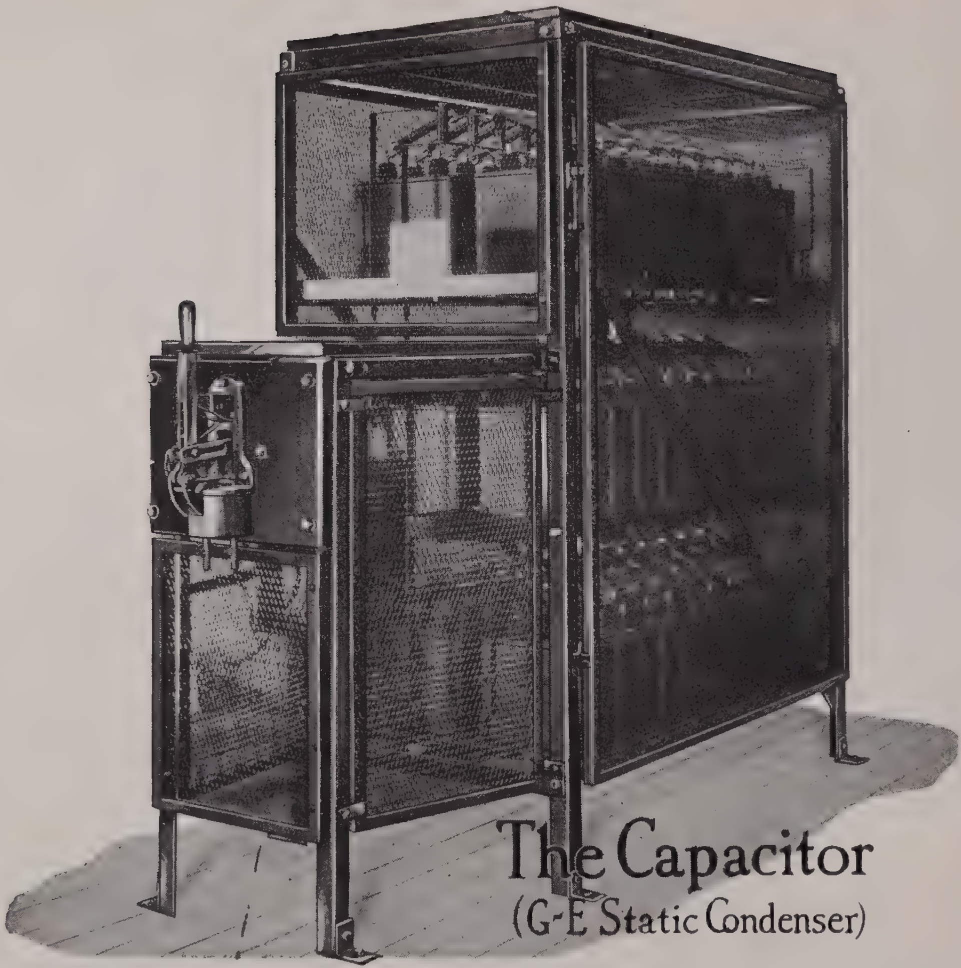

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for the ills of a system

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52-38

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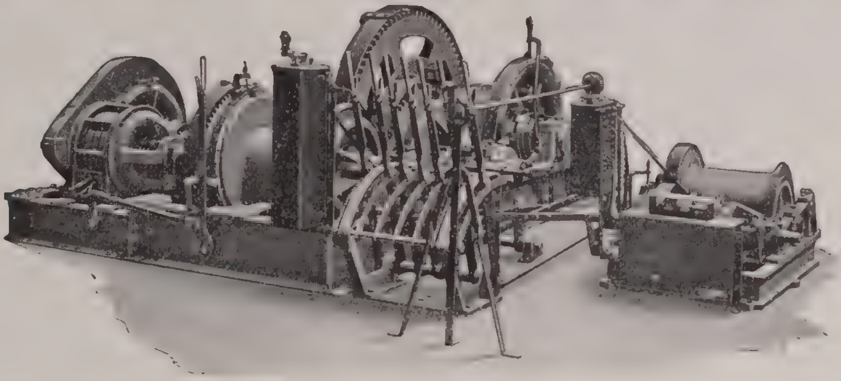

Illustration shows a two-speed electric quarry hoist with separate swinger, for operating bull wheel derrick. Hoists 35,000 lbs. on single line at 31 f.p.m., and 17,000 lbs. at 68 f.p.m.

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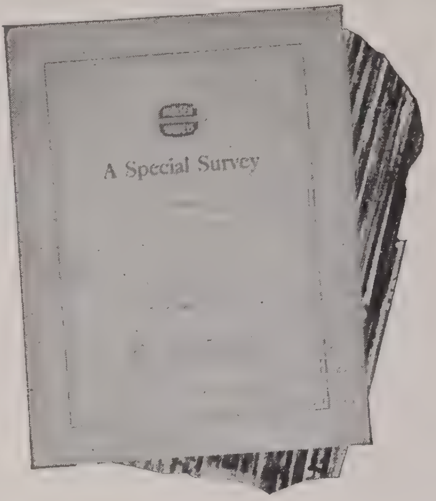

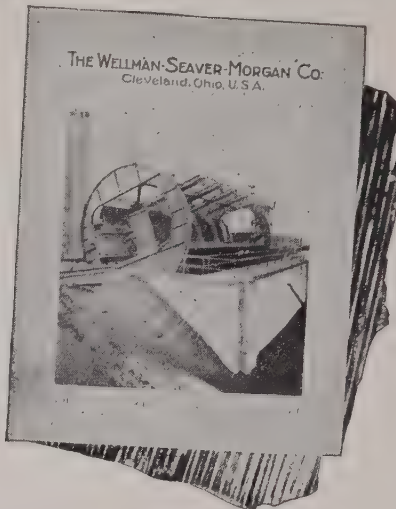

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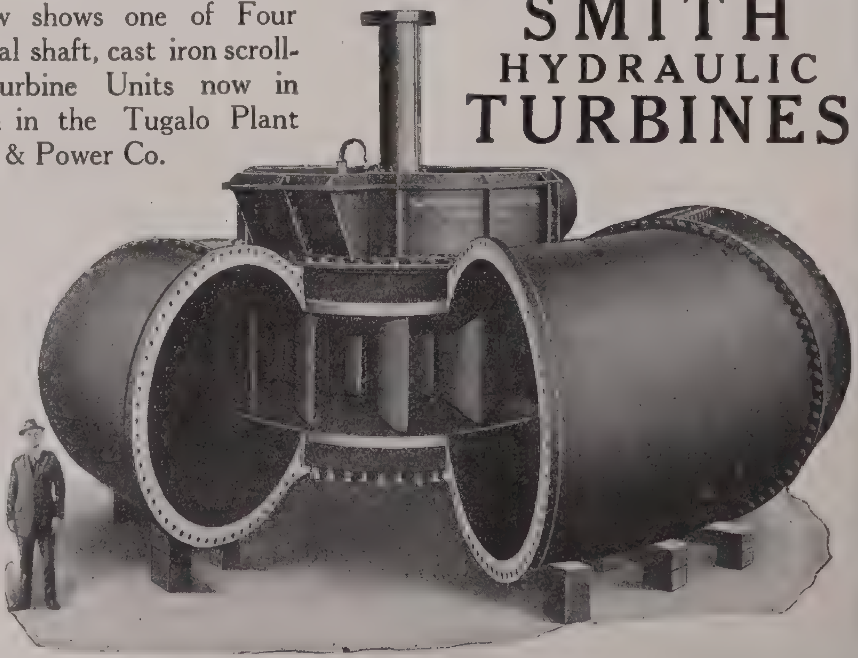

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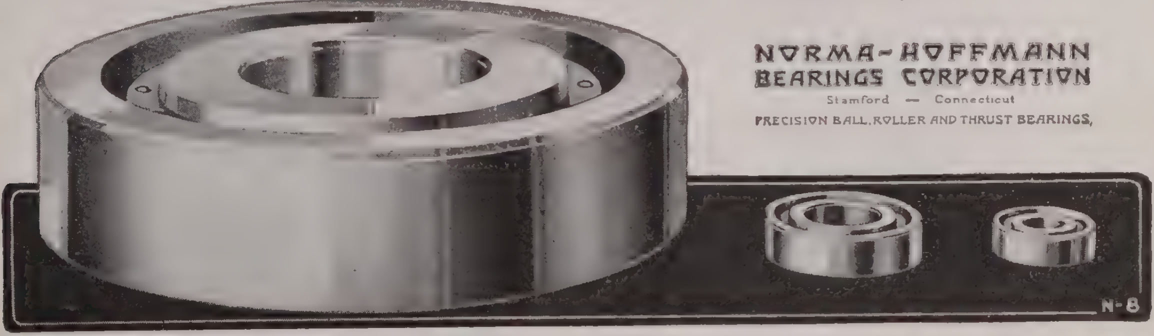
MAKE GOOD MOTORS BETTER

If the only loss from a worn-out, or burnt-out, sleeve bearing in a motor were the cost of replacement, it wouldn't be so bad—though bad enough.

But think of the shut-down losses on the production machines dependent for power upon that motor—the upset schedules, curtailed output.

"**Hoffmann**" Precision Roller Bearings in a motor, with Magazine Lubrication and with a factor of safety ample for every emergency, will prevent these losses due to motor bearing failure. Ask us to show you how and why.



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Double Galvanized Telephone and Telegraph Wire

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Non-Peeling—Non-Cracking

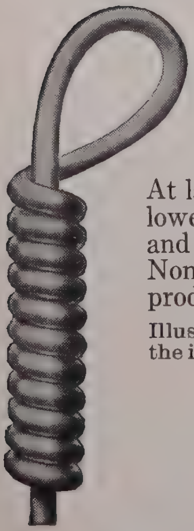

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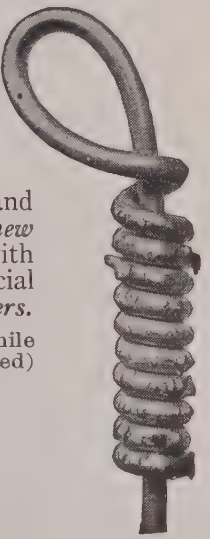
Illustration at right shows what happens to old process galvanizing, while the illustration at left shows assured results of CRAPO PROCESS—(patented)



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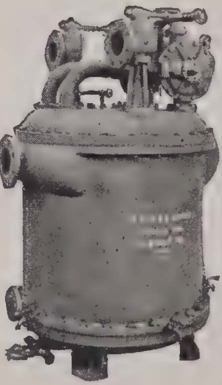

Radojet with Combined Surface Inter- and After-Condenser

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The latest development in the removal of air and non-condensable vapors and gases from condensers. High in efficiency because the steam from the first stage is condensed by the inter-condenser and the steam from the second stage by the after-condenser. In both cases the main condensate is used as the cooling medium. The condensed motive steam is returned to the hotwell where it is deaerated and pumped back together with the main condensate to the boilers. The extracted air does not come in direct contact with the feed water.

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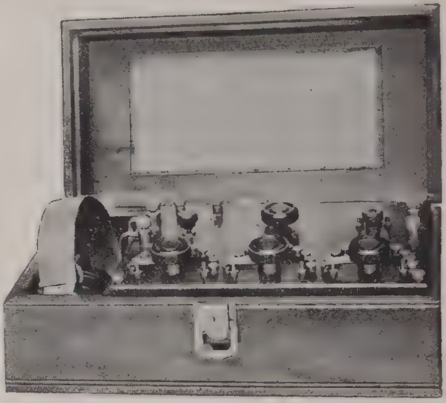

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Write for Bulletin G-1025

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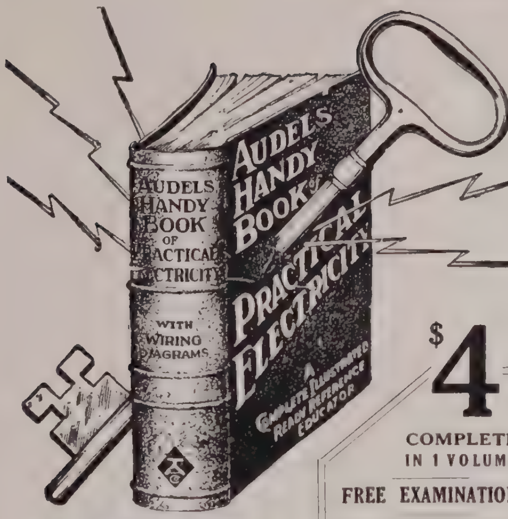
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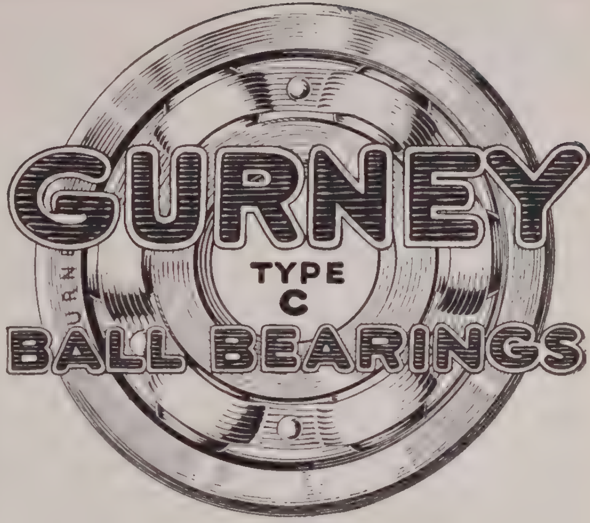

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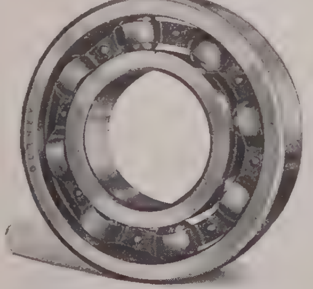

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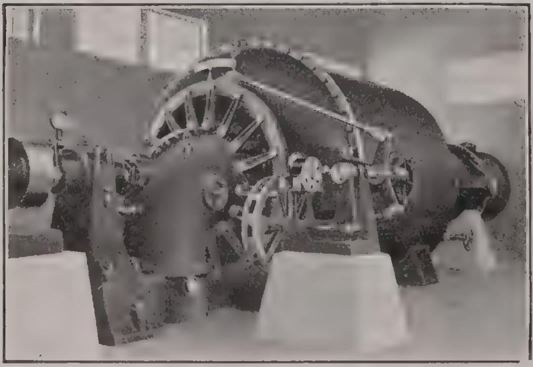

The illustration is that of a 600-h.p. Pelton reaction turbine of the horizontal shaft type installed by the San Joaquin Light and Power Corp. during 1918. It is self-regulating under an effective head of 39 ft., the only attendance being that of a watchman at intervals of six or eight hours for the purpose of adjusting the gate valve opening in accordance with the water quantity available.

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SALT LAKE CITY, 405-6 Kearns Building
SAN FRANCISCO, Sheldon Building
LOS ANGELES, 404-406 Central Building
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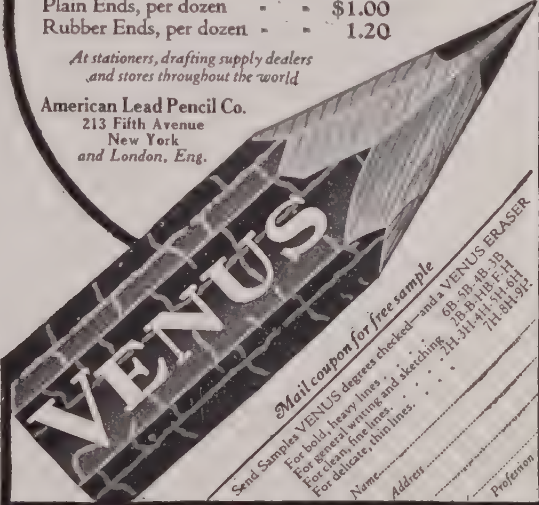

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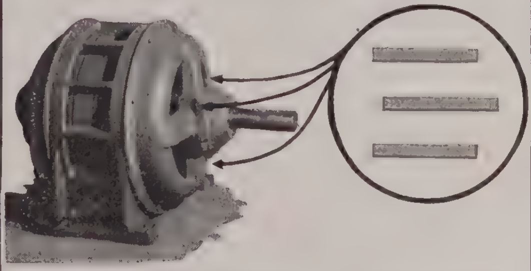

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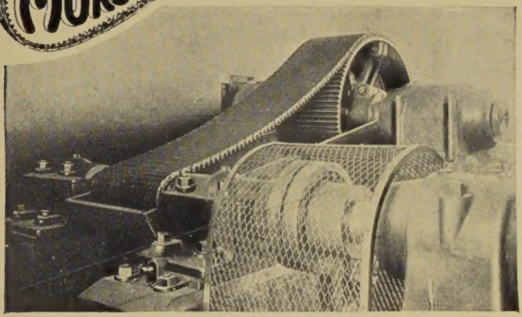

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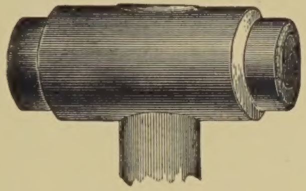

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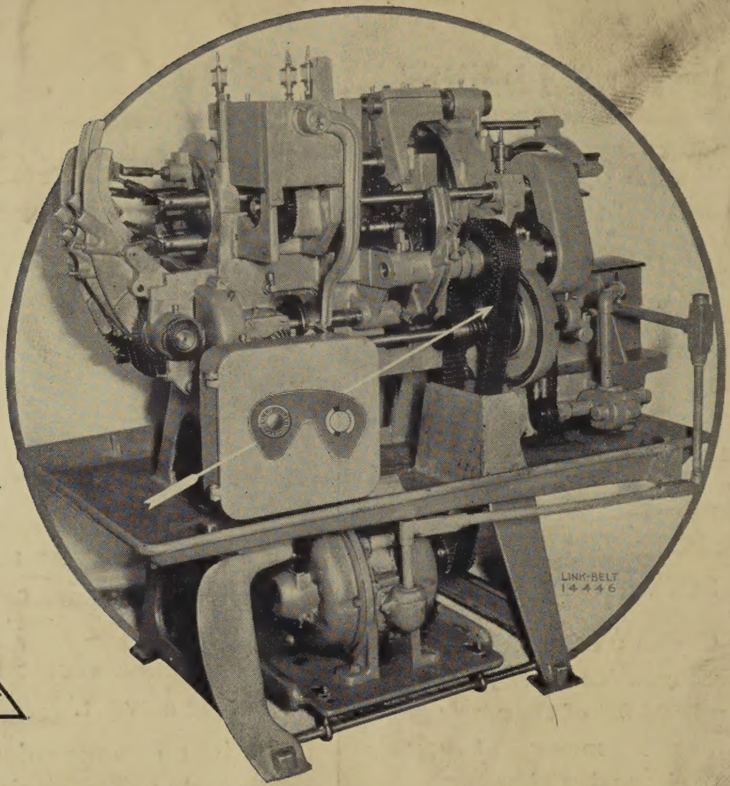

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